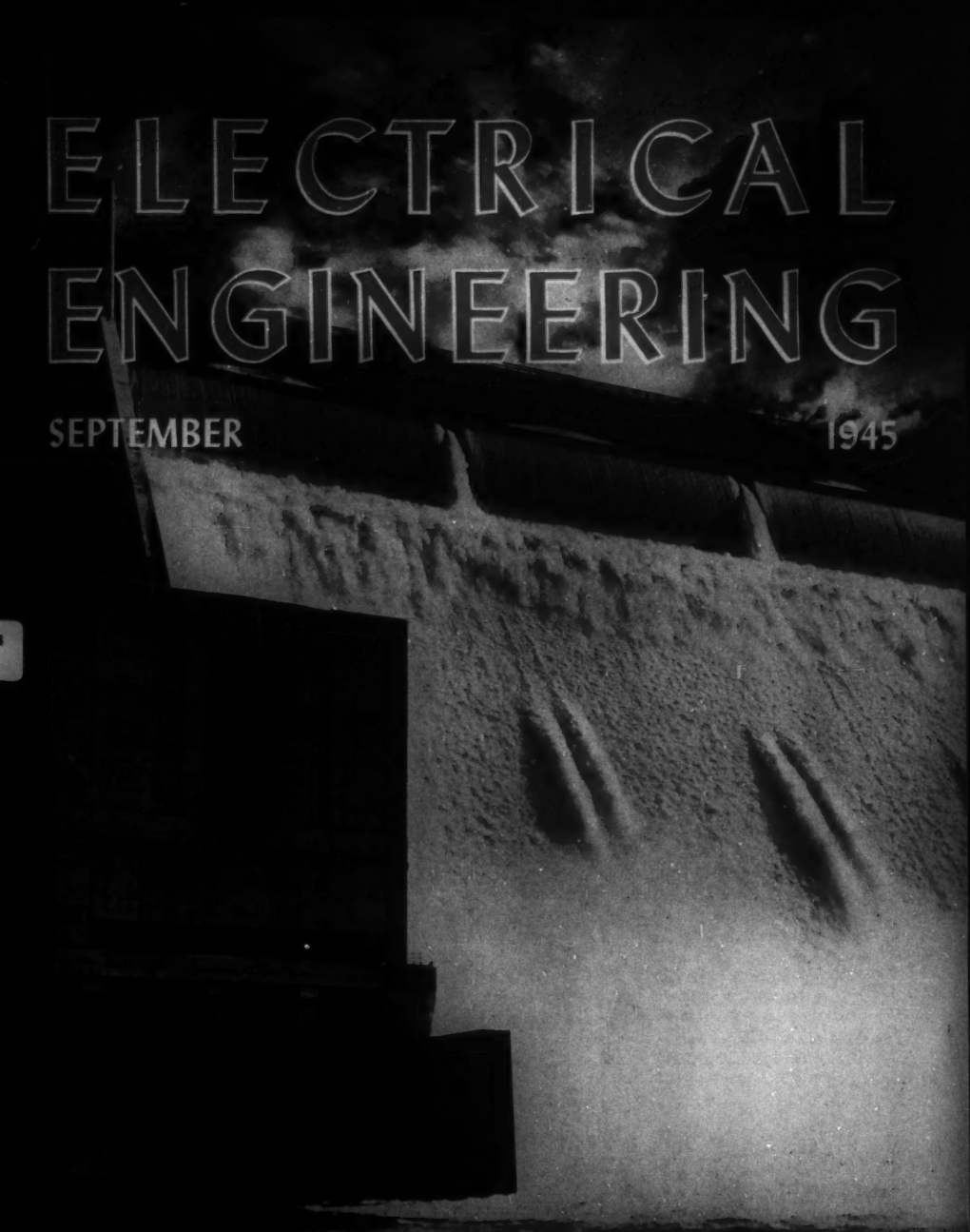
ELECTRICAL ENGINEERING

SEPTEMBER 1945



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Belden Wire Engineers give valuable advice on winding equipment, dereelers, coil finishing machines, coil impregnation, and baking. Their broad experience in magnet wire engineering also covers the selection of the best type of wire insulation for a particular coil winding job.

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is available in magnet wire Types F, HF, TF, and QF, either plain or in combination with textile or paper insulations. Try Belden Polyvar on your tough winding jobs.

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NATURAL AND SYNTHETIC ENAMEL AND TEXTILE INSULATIONS

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September 1945, Vol. 64, No. 9. Number of copies of this issue 27,200

POST-WAR BROADCAST EQUIPMENT—by G-R

● TWO of the first civilian products to come out of war research at General Radio are a broadcast station Modulation Monitor and a new Distortion & Noise Meter. These instruments have the latest circuits and new designs. Just as soon as we are out of war production these and other instruments for the broadcast station will be available again. Included will be a Frequency Deviation Meter, an F-M Monitor, a H-F Frequency Meter and Monitor, several Oscillators and other instruments. We are NOT in production on any of these now; however, information on several are available now. Brief descriptions are given below:

TYPE 1931-A AMPLITUDE MODULATION MONITOR

For program-level monitoring and for measuring transmitter audio-frequency response. Requires only 0.5 watt r-f input; carrier frequency range of 0.5 to 60 Mc; distortion is less than 0.1%; 600-ohm audio output circuit for audible monitoring; provides continuous indication of modulation percentage on either positive or negative peaks with a high-speed meter which reads both percentage modulation and decibels; measures carrier amplitude shift when modulation is applied; carrier envelope output available for distortion measurements; flashing lamp furnishes instantaneous indication of any modulation peaks exceeding any predetermined value between 0 and 100% on negative peaks. Approximate price: $220.00

TYPE 1932-A DISTORTION & NOISE METER

For measuring a-f distortion, noise and hum levels. Equally useful in the broadcast station, the development laboratory and the production line. Continuously adjustable from 50 to 15,000 cycles, fundamental, for distortion measurements and 30 to 45,000 cycles for noise and VU measurements; distortion ranges are full-scale for 0.3%, 1%, 3%, 10% or 30% with overall accuracy for each range of ±5% of full scale ±0.1% distortion; range for carrier noise extends to 80 db below 100% modulation or 80 db below a-f signal of zero VU level; no interlocking controls, only one tuning control plus small trimmer. Approximate price: $350.00

● WRITE FOR COMPLETE DESCRIPTION AND SPECIFICATIONS

GR

GENERAL RADIO COMPANY

Cambridge 39, Massachusetts

90 West St., New York 6 920 S. Michigan Ave., Chicago 5 1000 N. Seward St., Los Angeles 38

CABLE LIFE "PRE-VIEWED" BY OF EXPOSURE

Okonite's Proving Ground Duplicates Actual Operating Conditions

All kinds of weather and four kinds of soil provide thoroughgoing performance "pre-views" at the cable proving ground at The Okonite Company's Passaic, New Jersey plant.

About to start its ninth year of carefully-recorded cable service studies, this unique *outdoor laboratory* is dedicated to evaluating the useful life of all types of insulation both above and below ground under all severe operating conditions. Believing that time and time alone is the only true means of determining what a cable will do, Okonite engineers put principle into practice with the realistic creation of actual service conditions rather than artificial "accelerated aging".

Buried directly in various types of earth, pulled into conduit or installed overhead — network, control, primary distribution and portable power cables are constantly operating under controlled conditions of temperature, voltage and loading.

At specified intervals they are taken up, sections cut from the cable and detailed tests conducted under the independent supervision of The Electrical Testing Laboratories.

Test Conditions

Cables under test are installed in four concrete troughs, each 50 ft. long by 4 ft. wide and 4 ft. deep. These troughs, open at the bottom, are each filled with a different type of soil:

1. Top soil saturated with corrosive water from a manhole.
2. Soil with a layer of manure over the cables to simulate conditions of decaying organic matter.
3. A mixture of 99 lb. of sand and 1 lb. of lime which is subjected to a periodic pH test and maintained highly alkaline.
4. Soft-coal cinders regularly wet with a sulphuric acid solution to render them positively acid. Given a regular pH test and acidity maintained.

Cables in each trough are in two layers, Spacing of cables was selected to allow control and signal cables to be slightly warmed by network cables which are subjected to current loading. The majority of cables are buried between 30 in. and 36 in. deep.

Buried Since 1937

Four main types of cables are installed in the troughs in the proving ground.

1. Network cables. Nine cables representing all constructions, including fibrous and rubber covered; 250,000 circ. mil. single-conductor, insulated for 600 volts, operating at 120 volts and loaded in cycles nine hours a day, five days a week, to give a copper temperature of approximately 60 deg. C. Network cables in all troughs are in series across 120 volts.
2. Control cables. Eleven seven-conductor, rubber insulated cables with various types of metallic and non-metallic sheaths in each trough energized at 120 volts but not loaded.
3. Underground primary distribution cable. Four different commonly-used types of 5-kv. non-metallic sheath cable in each trough energized at 7.6-kv. but not loaded. Each trough contains 50-ft. lengths of each type of cable.
4. Portable high-voltage cable. Two types, shielded and non-shielded, 12.5-kv. three-conductor, dredge or shovel cables run at random in the yard on the top of the ground and moved each week. Two types are connected in series and ends connected to 12.5-kv. busbars.

In addition to the underground cables, two 30-ft. poles have been erected carrying more than a dozen types of insulated aerial cable and line and tree wire energized at 7.6-kv. from the busbar structure. Interconnecting these overhead "circuits" are three conduit risers on each pole containing four test cables each.

As tests are tabulated, valuable trends have already been disclosed. While eight years are too short for final conclusions, proving-ground results have indicated significant tendencies. For example, in the case of exposed cables, Okolite-Okoprene (Patent 2,312,058) is showing to advantage over the fibrous type of rubber insulated cable which has suffered braid deterioration, tape erosion and corona cutting.

This is but one instance — one forerunner of benefits to come. As time goes on and more and more facts accumulate, Okonite engineers will be guided to a greater degree by this recorded test data, and will pass along greater service-life knowledge in the form of improved electrical wires and cables. The Okonite Company, Passaic, New Jersey.

Underground portion of proving ground at end of first full year of operation.

Cables are periodically exhumed, sections removed, ends sealed for reburial.

OKONITE insulated wires and cables

Have you looked into METALLIZED GLASS?

YOUR electronic problems may find an answer in Corning's process for permanently bonding metal to glass.

Which of the following qualities will help you?

1. **Hermetic** bond between glass and metal — assures positive and permanent seal against oil, water, and gas.

2. **Precision** metallizing — allows accurate control of capacitance, inductance, or resistance.

3. **Permanent** mechanical and electrical qualities — maintain accurate tolerances indefinitely.

4. **Superior electrical properties** of glass — low power factor, high dielectric strength, extremely high resistance, wide range of dielectric constants.

5. **Thermal endurance** of a high order. Metallized glass easily meets Army and Navy specifications for thermal shock.

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Write us about your problems. We'd be interested in seeing if glass can help you. Address Electronic Sales Dept. N-9, Corning Glass Works, Corning, N. Y.

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They are particularly efficient in suppressing noise from dynamotors, generators, motors and other motor driven devices which might otherwise impair radio reception.

The illustrations show the rugged construction of the screw-type terminals to safely carry heavy currents. Units are encased in brass containers with a heavy tin dip—oil impregnated, filled, and hermetically sealed to meet the most severe operating conditions.

These capacitors can be supplied in the following capacities and voltage ratings: .01 MFD; .10 MFD; .25 MFD and .50 MFD—100 V. DC. or 500 V. AC/DC. Side or end BRACKETS are available with mounting holes in 3 sizes. Side bracket can be placed in either of two positions depending upon mounting requirements, and can be provided with mounting hole at various distances from center of terminal. Below is a partial list of these types.

Write for prints or any additional data on these or other units—we will be happy to serve you.

Standard or Special Units to Meet Every Need

FAST Capacitors are produced in many types and sizes in standard or special designs. We can supply paper capacitors—oil or wax impregnated—rectangular or tubular—in sizes from the smallest to the largest.

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CAP. MFD.	VOLTS	DIMENSIONAL DATA DIA.	LGT.	MOUNTING HOLE DIA.
.01	100 D.C.	11/16	13/16	7/32; 9/32 or 11/32
.10	100 D.C.	11/16	1-3/8	7/32; 9/32 or 11/32
.25	100 D.C.	5/4	1-9/16	7/32; 9/32 or 11/32
.50	100 D.C.	1	1-13/16	7/32; 9/32 or 11/32
.01	500 AC/DC	11/16	27/32	7/32; 9/32 or 11/32
.10	500 AC/DC	1	1-1/2	7/32; 9/32 or 11/32
.25	500 AC/DC	1	2-9/16	7/32; 9/32 or 11/32

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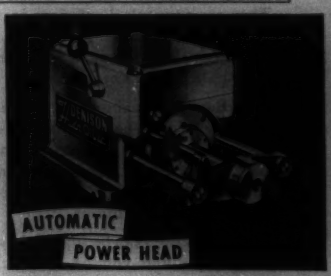
The Pump Unit includes electric motor, hydraulic pump, oil reservoir, and pressure regulating valve; and can be located at any convenient point. The Power Head incorporates fully-enclosed hydraulic cylinder, control valve, control lever, and the drive element (ram) which has a precision-type coupling device for attaching tools or the driven element. Length of ram strokes can be regulated anywhere between ⅛-inch and 6 inches. Ram pressures may be closely limited anywhere between 300 pounds and 4 or 6 tons. The Power Head can be positioned vertically, horizontally, or at any angle to suit the job. Two styles of these power heads are shown here: one with throttle-action control for feather-touch acceleration and deceleration of ram movement, and rapid or gradual increase and decrease of ram pressures; the other for automatic ram action, under which idling, single cycle, continuous cycling, dwell, and emergency reverse ram actions are available at a touch of the control lever. Still other Power Heads offer the revolutionary new Vibratory HydrOILic Pressure principle; rapid ram traverse and adjustable pressing speed; automatically repeated strokes of uniform pressure . . . and even a combination of *all* those actions. *Write today for full information on these standard Multi-Units!*

The DENISON Engineering Co., 1192 Dublin Rd., Columbus 16, Ohio

★ THROTTLE-ACTION CONTROL LEVER
★ PRECISION COUPLING DEVICE
★ STROKE-LIMITING SHIPPER ROD



★ 5-POSITION CONTROL LEVER
★ STROKE-LIMITING SHIPPER ROD
★ TELESCOPING RAM GUIDES
★ PRECISION COUPLING DEVICE

HydrOILics
INDUSTRY'S RIGHT HAND

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ENGINEERING COMPANY
Hydr OIL ics

As example of planned maintenance. After driving a sheet steel rolling mill for a score of years, the insulation of this stator was brittle, the varnish was dry and a coil had been cut out. To avoid the emergency which threatened, its owners selected the time it could best be spared and planned for its repair. Coils were produced and materials assembled in advance in our Columbus, Ohio, plant. The stator was taken off production Saturday. The old stator winding was stripped and a new one was installed. The rotor was cleaned, dipped and baked, rings were ground and the unit was dynamically balanced. The motor was back on the job the following Saturday.

WE'LL FIT ELECTRICAL REPAIRS TO *YOUR* TIME LIMITATIONS

Since it is often possible to forecast rotating electrical equipment trouble before the emergency occurs, why not plan the necessary outage for repairs ahead of the breakdown? Thus production which depends on the machine can be arranged to fit into the repair plans and needed materials can be prepared before the machine is taken out of service. Outage time is saved; production disturbance is minimized.

We are especially equipped to help you with this planned maintenance. If the work is to be done in your plant, we will have experienced field crews there on the job the minute current is cut off. For repairs in our plant, facilities are readied before your equipment is received. In either case, materials are produced in advance.

We can handle emergencies, of course — promptly, efficiently, economically — but our field engineers are at your service to help you *anticipate* trouble and to *correct* it before it causes extra expense and loss of time. Write, wire or 'phone.

NATIONAL ELECTRIC COIL COMPANY

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It is this Irvington policy of "*engineering* and *formulating* for specific applications," that accounts for the long service which Fibron plastic products provide . . . as well as for Irvington's continuing leadership in electrical insulation!

Fibron plastic tubings are produced in all standard opaque colors as well as transparent — diameters from .034" to 2" — in coils or cut lengths. Fibron tapes are obtainable in black and clear, in widths ½" to 3", thicknesses .004" to .030" and in convenient length rolls for hand application. Fibron wire markers are available plain or stamped, in inside diameters from .053" to ½".

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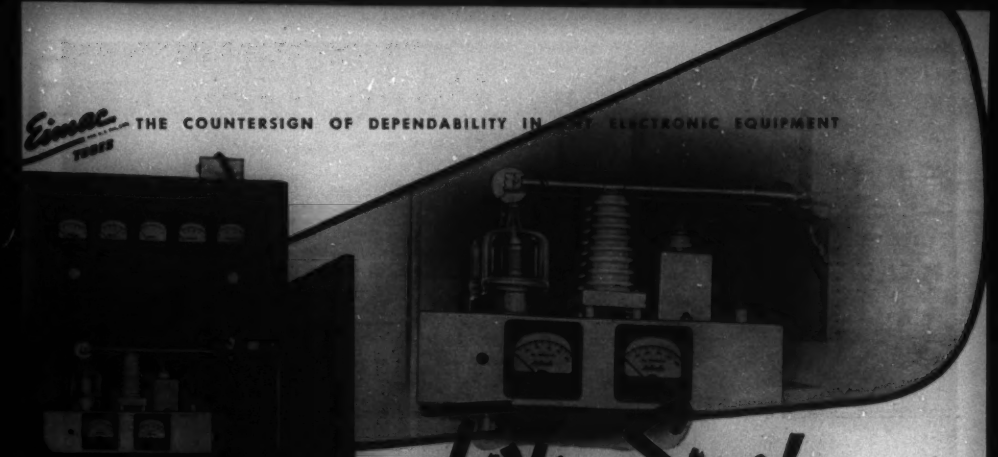
Eimac TUBES — THE COUNTERSIGN OF DEPENDABILITY IN ELECTRONIC EQUIPMENT



Top Spot

IN FM POLICE SYSTEMS

EIMAC TETRODE 4-125A

view of the 250-118 mc. Motorola mitter, now giv-Miami police the st of coverage for dius of 30 miles.

Top honors to Galvin Manufacturing Corporation for building it, and a salute to the police and fire departments of Miami, Florida, for putting it to work in spite of the skeptics! It's the first two-way police radiotelephone system in the United States on frequencies *above 100 mc.* Twenty-four hours a day, 12 patrol cars in Miami's busy area tune in on signals as solid as a dinner-table conversation from this Motorola 250 watt, 118 mc. FM transmitter.

From the earliest experimental stages of FM broadcasting, Eimac tubes have been lending a hand. Naturally, there are Eimac 4-125A tetrodes (pictured above) in the vital power output stage of Galvin's new Motorola success. Eimac 4-125A's were a logical choice for this transmitter because of their superlative high frequency performance capabilities and their low driving power requirements.

FOLLOW THE LEADERS TO

Eimac TUBES

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1074

ELECTRICAL CHARACTERISTICS - 4-125A TETRODE

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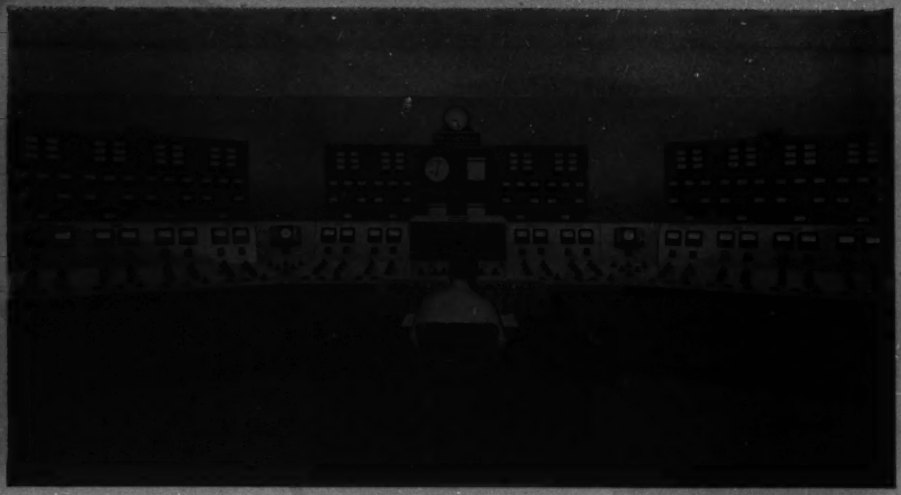
Voltage . . . . 5.0 volts	Grid-Plate (Without shielding,
Current . . 6.2 amperes	base grounded) . . . . 0.03 μμfd.
Plate Dissipation	Input . . . . . 10.3 μμfd.
(Maximum) 125 watts	Output . . . . . 3.0 μμfd.

Transconductance (ip = 30 ma., Eb = 2500 v., E_{c2} = 400 v.) . 2450 umhos



Switchboard in Control Room of Aluminum Co. of Canada's Shipshaw Powerhouse. Note how signal lights and Micromax Recorders are centralized in operator's triangle of vision, with all switches for the Stations hydro-generators at the sides.

SHIPSHAW OPERATOR

Watches Generators via Micromax Recorders

The instruments in Shipshaw Powerhouse's Operating Room are noteworthy for the quick, compact way in which they enable the generation operator to watch the Station's three interrelated conditions of frequency, load and generator temperature.

The Round-Chart Micromax Recorder, just below the clock at the left, shows the frequency.

Beside the Round-Chart Frequency Recorder is a Micromax Strip-Chart Load Recorder. This instrument totalizes the megawatt output of Shipshaw's twelve units.

Below the Frequency and Load Recorders are two Micromax six-point Generator Temperature Recorders; only the top halves are visible in the photograph. Each shows the stator temperatures in 6 generators, and warns if the ultimate load-limit is reached, regardless of power factor, ambient temperature or any other contributing factor.

Thus the four Recorders tell the story of what the twelve turbo-generators are doing, and tell it in the way best calculated to help the operator perform his twin duties of carrying the station load and protecting the machines.

Any or all of these L&N publications will be sent on request, but if you have a problem to which an L&N Recorder or Controller may be applied, we suggest you call in an L&N engineer for specific recommendation.

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ELECTRICAL ENGINEERING

Registered United States Patent Office

SEPTEMBER
1945

The Cover: Grand Coulee Dam, which develops 1,300,000 horsepower for the west coast of the United States, will eventually produce more than 3,000,000 horsepower. Two huge Allis-Chalmers hydraulic turbines, designed for California's Shasta power plant, were adapted to Grand Coulee design.

Allis-Chalmers Manufacturing Company photo

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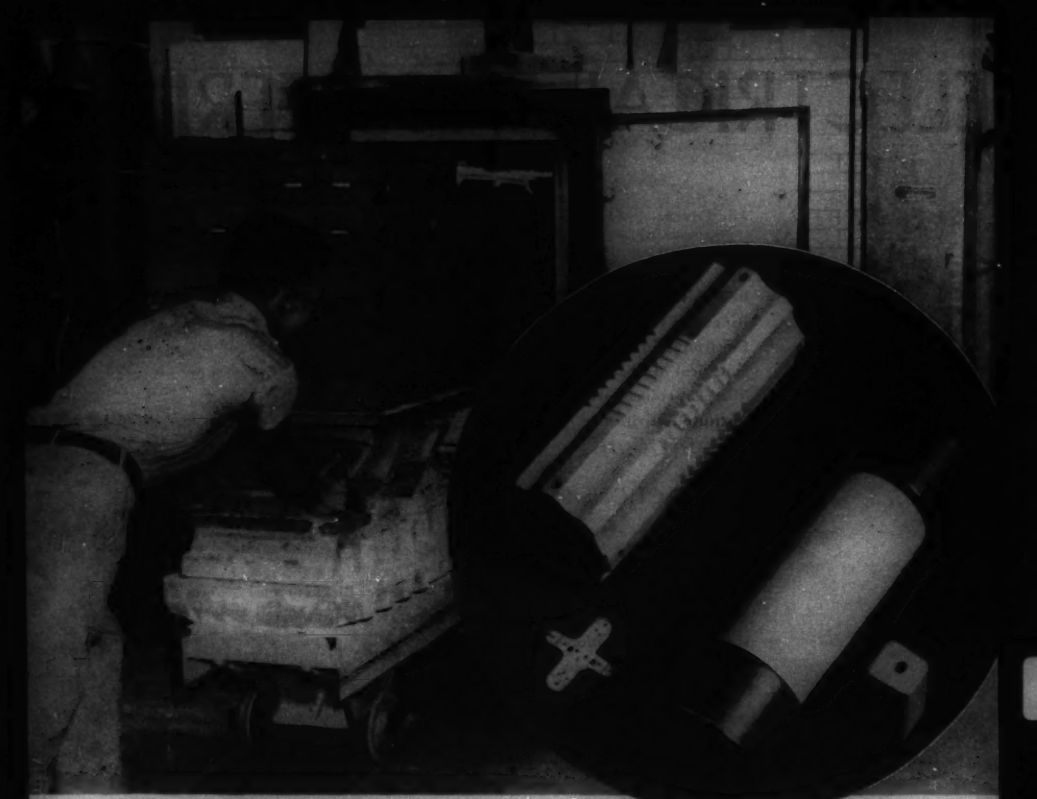

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ELECTRICAL ENGINEERING

VOLUME 64, NUMBER 9 SEPTEMBER 1945

Beginnings of Nuclear Physics

K. K. DARROW

Comparison of the field of nuclear physics and electronics; an analysis of the charges and masses of the nuclei in line with the nuclear theory; definition and description of the process of transmutation and its reactions and creations, namely, radioactive substances and stable nuclei, are the main points discussed in this article.

AS I UNDERSTAND the terms of my invitation, I am to introduce to you a topic which cannot claim to be a part of electronics, unless on the Tennysonian principle—"I am a part of all that I have met." Nuclear physics has indeed met with electronics, to its considerable gain; for some of its most essential measuring devices and auxiliary gadgets belong to the field of this conference. There is even a more intimate relationship, for nuclear physics has the privilege of watching over the birth and the death of electrons; yet out of all the myriads of electrons which you administer, I suspect there are only a few of which it has been the godfather and I hope there are only a few of which it will see the extinction. By and large, nuclear physics pertains to the massive, the heavy, the inert and the comatose parts of matter, while electronics pertains to the lightweight, the sprightly and the nimble parts. You will learn, however, that given the right circumstances and the proper assistance, the inert parts of matter can become exceedingly sprightly, and exchange their state of coma for a quite remarkable liveliness.

What are these parts of matter, to which I have been condescendingly referring as "inert" and "comatose"? Well, you all know that according to modern views, every atom of matter consists of a nucleus with a positive charge, and a swarm of negative electrons which are constrained by that positive charge to stay around the nucleus. The electrons are your servants, and the nuclear physicist does not try to tempt them away from their allegiance to you. They do him the good office of indicating the size of the positive charge on the nucleus; for this is equal to the sum of the charges on the electrons, and it is easier to count the electrons than to measure the nuclear charge directly. Thanks to the electrons, we know the charges on the nuclei of all of the chemical elements. If you look at a modern table of the elements, and not at one of those grimy old wall maps that used to hang in chemistry lecture rooms before World War I, you will see these charges indicated by a prominent number next to the symbol of every element. This number is 1 for hydrogen, 2 for helium, 3 for lithium, 4 for boron, and so on up to 92 for uranium, the last and heaviest element of the periodic table. It is the charge on the nucleus expressed as a multiple of the electron-charge e, and we call it the "atomic number."

These atomic numbers are not, however, the only numbers which are juxtaposed to the symbols of the chemical elements, in a modern or even in an ancient table. In fact if you go back to the old tables of the pre-World-War era—and I regret that even now it is not so difficult as it should be to find one still doing its superannuated duty on a wall—you go back to an era when atomic numbers were unknown, and yet you find a number affixed to every element. This, of course, was the "atomic weight." Now I have introduced the second feature of the nucleus: its weight, or mass. My reason for disparaging the nucleus as being heavy and inert was simply, that it has nearly the entire mass of the atom. In fact, there is no atom for which the masses of all the negative electrons put together amount to as much as one one-thousandth of the mass of the nucleus. That is why I said at the beginning of this talk that electronics has the lightweight, the sprightly and the nimble parts of matter to play with. Or to use another analogy, you get the froth and nuclear physics gets the potent part.

You may now expect me to say, or indeed you may feel that I have said already, that the ancient tables give the masses of the nuclei, at least to within one tenth of one per cent, under the old-fashioned name "atomic weight." This would indeed be true, apart from minor errors in measurement, but for one important fact. Each element, with only a few exceptions, is a mixture of atoms of several different kinds with different masses. We call them "isotopes." If an element has only one isotope, like fluorine or beryllium for instance, then the chemical atomic weight does give very nearly the mass of the nucleus. But in the much commoner case of an element with two or several isotopes, the chemical atomic weight is just a sort of weighted mean of the masses of two or several different kinds of atom.

Such a weighted mean is of almost no interest to the nuclear physicist, but fortunately he has methods—the earliest goes back about 32 years—for measuring the masses of the individual isotopes. A really modern table of the elements will display, next to the symbol of each element, not only its chemical atomic weight which is still of value to the chemist, but also the weights of its individual isotopes which are of great concern to the nuclear physicist. This of course begins to make such a table a pretty rich and copious affair.

The time has come for pinning down these generalities with some examples. I repeat that we are now concerned with the charges and the masses of the nuclei, and I soon will make clear how greatly they merit our concern. My examples will be taken from the simplest nuclei, which are those of the lightest elements, the elements at the commencement of the periodic table.

Hydrogen is the first of the elements. Its nuclear charge is fixed by the very well-known fact that the hydrogen atom has only one electron. This charge is therefore equal to the charge of the electron, and is positive in sign. In other words, the nuclear charge of hydrogen, when expressed in terms of the electron-charge e as unit of charge, is $+1$. In still other words, the atomic number of hydrogen is 1. We put this down as the first item of information about hydrogen nuclei.

Now for the nuclear mass: the old tables say that the atomic weight of hydrogen is 1.008, but this is just a weighted mean of the masses of the two isotopes

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Essential substance of an address delivered at the National Electronics Conference, Chicago, Ill., October 5-7, 1944, and published in *Proceedings* of the National Electronics Conference, volume 1, 1944.

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called "light hydrogen" and "heavy hydrogen," respectively. The actual atomic masses by recent measurements are found to be 1.0081 and 2.0147. I give these values to five significant figures, all of which are believed to be sure; I deduct 0.0005 for the mass of the electron which is part of every complete hydrogen atom, and write 1.0076 and 2.0142 for the masses of the two kinds of hydrogen nuclei. Now an omission must be rectified. I have told you that the values of nuclear charge are given in terms of e as unit of charge, but I have not yet told you the unit of mass in terms of which these nuclear masses are expressed. This unit of mass is one sixteenth of the mass of the commonest kind of oxygen atom. Both units are very small, compared with those of ordinary usage: the electrical one about 10^{-19} of a coulomb, and the other about 10^{-23} of a gram. The reason for this extravagant smallness of the units is that the nuclear physicist talks about individual atoms and individual nuclei, while the chemist talks about gram-molecules of atoms and the electrical engineer talks about legions of electrons. It is in fact one of the characteristics of the nuclear physicist, that often he observes and even measures an event in the life of a single nucleus.

Next, it will be convenient and indeed essential to adopt some names or symbols for these nuclei. As it happens, the two which I have just introduced to you have names: "proton" and "deuteron" for the nuclei of light and heavy hydrogen, respectively. But there are about 600 different nuclei, and if they all had names our memories could hardly stand the strain. To make a symbol for a nucleus, we begin by putting down the chemical element to which it belongs—H for hydrogen, in this instance. Then at the lower left we put the atomic number, 1 in this instance, so that the symbol becomes $_1$H. Now we have introduced a superfluous bit of luxury, since the chemical element determines the atomic number and vice versa; but it often is regarded as good practice to hammer an idea in by repetition, and that is what we do when we give both the atomic number and the chemical symbol. Lastly we put, at the upper right, the nuclear mass—but not to all the five or six significant figures which the measurements permit. We need not be perpetually reminded of the exact masses: we shave off all the figures to the right of the decimal point, and write $_1$H^1 and $_1$H^2 for proton and deuteron, respectively.

With the aid of this notation, I now introduce you to four more nuclei. The second of the elements is helium. Its nuclear charge is $+2e$, its atomic number is 2, and it has two isotopes of which the nuclear masses are 3.0161 and 4.0029, respectively. The symbols for these two nuclei are $_2$He^3 and $_2$He^4, respectively. The latter is one of the few which have names of their own: it is called "the alpha particle." The third of the elements is lithium, having two isotopes of which the symbols are $_3$Li^6 and $_3$Li^7. The nuclear masses of these two are given as 6.0154 and 7.0177.

THE NUCLEAR THEORY

The next step is, to introduce a model for these nuclei. As we take this step, theory rears its head. Nuclear theory has a bad reputation, which some portions of it deserve; but it commences with a very simple and effective postulate, and you have no cause for alarm over what happens to the nuclear theorist in his further explorations, for I shall not be leading you so far.

Going back to the proton for our start, we are to accept it as an elementary particle. I represent it by a circle with a cross inside to indicate the positive charge: ⊕. You may visualize it as a sphere.

Going on to the deuteron, our program is to represent it in the simplest conceivable way. This way consists in imagining the deuteron as a pair of particles stuck together, one being the proton, while the other perforce must have about the same mass as the proton but no charge at all. Let us postulate such a particle, give it the name of "neutron" by allusion to its lack of charge, and represent it by a circle without a cross inside, ○. Now the model of the deuteron is this: ⊕○.

The grand simplicity of nuclear theory is, that we are permitted to go all the rest of the way and to model other nuclei however massive, with no more building-blocks than just these two, the proton and the neutron. Thus, the other four nuclei which I have individually mentioned are to be depicted thus: ⊕⊕○ for $_2$He^3, ⊕⊕○○ for $_2$He^4, ⊕⊕⊕○○○ for $_3$Li^6 and ⊕⊕⊕○○○○ for $_3$Li^7. Notice that such a symbol as $_3$Li^6 carries on its face the prescription for making the appropriate model. The figure on the lower left is the number of protons, and the figure on the upper right is the number of particles altogether, the sum of the protons and the neutrons. One would probably not enjoy the task of drawing a cluster of 226 circles and putting crosses into 88 of them, but the symbol $_{88}$Ra^{226} (for the nucleus of radium) relieves us of that. It tells us how many circles and crosses we ought to put down if we were doing it, and the rest we can leave to the imagination. I mention here that we are to call the total number of circles or of particles, protons and neutrons together, by the name of "mass-number."

My next duty is to introduce to you the neutron, no longer as a merely hypothetical particle but as a real one. The word "real" is a rather dangerous one for a physicist to use, and I hope that there is no professional philosopher in the room who would be nasty enough to insist that I justify my use of it. All that I want to imply is, that nuclear physicists are very well acquainted with the "free" neutron, not attached to a proton or to anything else, but rambling around by itself in empty space as freely though not so securely as any molecule of gaseous air. Of both of our building-blocks, neutron as well as proton, it can be said that they are independently known. I could have avoided saying that we make nuclear models by adding hypothetical neutrons to actual protons; the two are on the same footing, and actually the nuclear models that I have been sketching for you were not believed in, until the two were both established on the footing of experiment.

So, let us now add the neutron to our list of nuclei, at the beginning where it belongs. Its symbol must tell that its charge is zero; also, that its mass number is 1, for as I have lately told you it has about the same mass as the proton. The symbol is accordingly $_0$n^1. What is the accurate mass, as distinguished from that approximation which we call the "mass-number"? I go to the most recent tables, and I find 1.0089.

Now surely we have all the material necessary for predicting the masses of all nuclei. I add the 1.0076 of the proton and the 1.0089 of the neutron, and I get 2.0165, which must be the mass of the deuteron. I double this figure to get the mass of a cluster of two neutrons and two protons, and arrive at 4.0330, which must be the mass of the alpha particle. The figures seem irreproachable, and yet they have lied. The masses of the deuteron and the alpha particle are 2.0142 and 4.0029. Have these values been badly determined? Not so! They are very well known. Could it be that the mass of the free neutron has been badly determined, or that the free neutron of experience is after all a different particle from the hypothetical neutron of nuclear structure, so that for the mass of the latter we should have chosen a different value? We cannot get anywhere along this route, for if this were the whole trouble the mass of the alpha particle would have to be twice that of the deuteron, 4.0284 instead of 4.0029. Apparently there is something very wrong. But actually there is something very right; and now we have reached the most important single point of this discourse.

The point may be paraphrased as follows. If one assumes that a body is made up of particles, one is perforce assuming that the particles stick together. "Stick together" is of course a layman's term; a physicist will say that energy must be supplied to tear the particles apart. But as Einstein told us long ago, energy is always weighted down with mass, and accordingly the mass of the system of particles must increase when they are torn apart. Reverse the process (in thought). When the particles come together and stick and form the body, its mass must be smaller than the aggregate of the masses which they had while they were free. Thus when we figure out the sum of the masses of all the protons and all the neu-

trons that go into a nucleus and find it greater than the mass of the nucleus—as we always do find it to be—that is no disaster, but a welcome discrepancy. Instead of contradicting the theory, it is just what the theory needs.

The discrepancy or deficiency of mass is called "the binding-energy of the nucleus." This is a defective name, which ought to be improved. The quantity in question, the deficiency of mass of the whole compared with its parts, ought to be called the "binding want-of-energy of the nucleus." You notice that now I am using "mass" and "energy" as though they were synonymous. This is one of the habits of nuclear physicists, and on the whole it is a sound one. As a consequence, nuclear physicists get into the habit of using the units of mass and energy indifferently, with reference to the very same thing. For instance you will hear them say that the mass of the proton or the neutron is around a billion of electron-volts, or that the mass of the electron is around half-a-million. The unit of mass which I have been using amounts, on the energy scale, to 931,000,000 electron-volts. The binding want of energy of the deuteron, 2.0165 less 2.0142, is accordingly about 2,200,000 electron volts and that of the alpha particle, 4.0330 less 4.0029, has the considerably greater value of some 28,000,000 electron volts. We note that in the alpha particle, the constituents lose on the average three quarters of one per cent of their mass; this is about as great a proportionate binding want-of-energy as is ever observed.

Bear with me for one more step which I promise you shall take us on to transmutation, the topic above all others which I suppose has drawn you hither.

Consider two protons and two neutrons. First, let them be united into a pair of deuterons: ⊕○, ⊕○. This assemblage has a total mass of 4.0284. Now suppose they are regrouped into a cluster of two protons and one neutron, plus a free neutron somewhere else: ⊕⊕○, ○. This assemblage has a total mass of 3.0161 plus 1.0089, or 4.0250. Call them the "first grouping" and the "second grouping," respectively. The second grouping compared with the first has a mass (or energy) smaller by 0.0034 of a mass-unit (or 3,170,000 electron volts). Nuclear physicists in their exchangeable currency of mass and energy have the habit of describing the big coins in mass-units and the small change in energy-units, so they would commonly say that the mass of the second grouping is less than that of the first by 3,170,000 electron volts.

You see, of course, that the four particles can never go from the second grouping to the first unless energy is administered to them from the outer world. They can shift over from the first grouping to the second without any such contribution, and moreover they have a tendency to do so. Here is the basic principle of transmutation: protons and neutrons have a tendency to go from one to another grouping, if when they do so there is release of energy. Some of you will be reminded of an ancient principle of chemistry, to the effect that a chemical reaction tends to take place provided it involves the release of energy. Actually this is not quite the statement now accepted in chemistry, in which science it has been found necessary to substitute the concept of "free energy" for that of plain energy; but in nuclear physics we still content ourselves with the older form of the principle. The tendency, then, exists; but apparently it is not usually sufficient—some obstacle has to be overcome, some opportunity provided. How then shall we give opportunity for the component particles of a pair of deuterons to follow their tendency, and regroup themselves with release of energy into the second grouping?

The essential is obviously, that the deuterons shall be brought close together—or let me say for vividness, they must be brought into contact with each other. To this however there is an obstacle, arising from the positive charges on the deuterons. Both being of the same sign, they repel one another in the normal manner of electrostatics; and if two deuterons were to approach one another with the ordinary speed of thermal agitation, they would turn back in their tracks and recede from one another without ever getting even nearly into contact. To get them into contact, the nuclear physicist must drive one of them against the other—or if you prefer, he must project, precipitate, throw, or hurl one of them against the other; or rather, since he cannot work with just two and wouldn't want to anyhow, he must bombard a flock of stationary deuterons with a stream of high-speed deuterons, hoping that a perceptible fraction of the impacts will lead to contact and to the spontaneous regrouping.

As you already know, or have divined, the hope is justified if the bombarding deuterons are driven hard enough; and this is the purpose of the high-voltage engines, the cyclotrons and the electrostatic generators and the transformer-rectifier sets, which dominate the laboratories of the so-called "atom-smashers." I cannot give you a precise figure for the minimum voltage which is required for bringing the deuterons into contact, for there is no sharp minimum voltage. If the voltage is 1,000,000, and the energy of the bombarding deuterons accordingly 1,000,000 electron volts (this is the definition of 1,000,000 electron-volts!) the "yield" of this process of regrouping is quite ample for easy observation. The energy of the impinging deuteron adds itself onto the 3,170,000 electron volts released by the regrouping, and the sum total turns up as kinetic energy of the cluster of particles ⊕⊕○ and the isolated neutron ○.

I have been depicting this process by models—now let it be represented in symbols. The cluster ⊕⊕○ is evidently the nucleus ${}_2He^3$ which has already been mentioned. The isolated neutron has the symbol ${}_0n^1$, and the process is written thus:

$${}_1H^2 + {}_1H^2 = {}_2He^3 + {}_0n^1 + 3.17 \text{ MEV}$$

Two nuclei of hydrogen have disappeared; one nucleus of helium and one free neutron have appeared in their place, and 3,170,000 electron volts, which previously existed as part of the mass of the deuterons, has been transformed into kinetic energy of the helium nucleus and of the neutron. This is a "reaction of transmutation," and the descriptive equation is an equation of "nuclear chemistry," similar in aspect to the equations of ordinary chemistry but of a kind which would horrify any chemist of the pre-World-War era, could he but come back and look upon it.

On this example I can base a sort of combined definition and description of the process of transmutation—Transmutation occurs when two nuclei are brought into contact with one another, and is a process in which the original protons and neutrons regroup themselves into two newborn nuclei with a release of energy.

Not every case of transmutation conforms to this description although great numbers of them do. There are also cases in which the impinging nucleus unites itself with the nucleus which it strikes, the energy which is released being carried off by a corpuscle of light. There are also cases in which the impinging body is itself a corpuscle of light; thus, the deuteron itself may be divided into a free proton and a free neutron, by administering to it a corpuscle of light which has energy enough to fill up that deficit of mass or binding want-of-energy of 2,170,000 electron volts which so-to-speak has been holding the deuteron together. There also are cases in which two neutrons and two protons, bound together into an alpha particle, release themselves spontaneously from a much more massive nucleus, because the mass of that original nucleus is greater than the sum of the masses of the liberated alpha particle and of the residual nucleus which the alpha particle leaves behind. This last case is exemplified by radium, and what I have just given you is the description of the radioactivity of radium. There are still other cases.

When a pair of deuterons is driven into contact, something different may happen from what I have just been describing. You may expect me to say that sometimes the deuterons unite themselves into a single alpha particle. This would indeed entail a wonderful release of energy, but apparently it does not happen. There is something or other to prevent it, and also there are inhibitions on various other conceivable reactions of transmutation which also would entail a release of energy; we can only hope that nuclear theory will be able to explain them. The alternative

thing which sometimes does happen, when deuteron meets deuteron, is represented thus by model:

$$\oplus\bigcirc \text{ and } \oplus\bigcirc \text{ into } \oplus\bigcirc\bigcirc \text{ and } \oplus \qquad (1)$$

The four particles regroup themselves into a cluster of one proton and two neutrons, and a free proton off by itself. Evidently then this grouping has a smaller mass and energy than the first grouping into a pair of deuterons. Writing the process as an equation of nuclear chemistry, we have:

$$_1H^2 + {}_1H^2 = {}_1H^3 + {}_1H^1 + Q \qquad (2)$$

in which Q stands for the release of energy.

This process leads to a free proton, and also to a nucleus of an isotope of hydrogen which has not yet been mentioned in this discourse. I left it out deliberately, because it has a feature which sets it apart from the six atom-nuclei which I did mention. It is unstable and it is radio-active—two words which are almost, though not quite, synonymous in nuclear physics. The manner of its radioactivity is this. After a lapse of time which may be months or may be years or may be very short, such a nucleus emits a negative electron. Incidentally it thus becomes a contributor to electronics, and you should be grateful for its contribution, though if all the electrons contributed by $_1H^3$ nuclei in the history of the world were gathered together I do not think they would supply a pentode very long.

Where does this nice fresh electron come from? Following the theorists of today, I have told you that there are no electrons in a nucleus, nothing but protons and neutrons in fact. There was indeed a time—it extended up to 1932—when the theorists did assert that there are electrons in the nucleus. I will not swear that no such time will ever come again, for the flexibility of theorists is something wonderful. However, at present we regard the nucleus as consisting of protons and neutrons exclusively, and this policy has so many advantages that we gladly accept its corollary, which is, that the electron comes into being at the moment when it starts out from the nucleus. If this seems absurd to you, I remind you that it is the assumption you all make in regard to light. Atoms emit light, and yet you do not suppose that there are corpuscles of light running around inside atoms all the time. You suppose that the atom releases energy and that this energy takes the form of light as soon as it escapes; and you are expected to make the same supposition about the nucleus emitting the electron. I hope you are satisfied with this doctrine, because for the present at least it is the doctrine which you have to take.

Let us now envisage the condition in which the departure of the electron leaves the former $_1H^3$ nucleus. The electron took off a charge $-e$ from a nucleus which already possessed a charge $+e$, and which accordingly now possesses a charge $+2e$. The newborn nucleus is therefore an isotope of helium. The electron also took along its mass, which however is only 0.0005 of a mass-unit, and the mass of its kinetic energy which also is small. The mass-number of the newborn nucleus is therefore the same as that of $_1H^3$, and its symbol must be $_2He^3$. The equation is:

$$_1H^3 = {}_2He^3 + (\text{neg. el.}) + E \qquad (3)$$

in which E stands for the kinetic energy of the negative electron (plus the recoil energy of the newborn nucleus, which is slight). The model is:

$$\oplus\bigcirc\bigcirc \text{ into } \oplus\oplus\bigcirc \text{ and (neg. el.)} \qquad (4)$$

so that in effect we assume that when the negative electron departs, one neutron turns into a proton.

Is the $_2He^3$ nucleus at which we have arrived just the same as the $_2He^3$ nucleus of which I earlier spoke, the one which is derived directly from an alternative reaction between deuterons? Let me indicate how this question might be answered. By measuring the kinetic energies of the $_1H^1$ and $_1H^3$ nuclei resulting from the process 2, we can evaluate Q of equation 2, and then solve the equation for the mass of $_1H^3$ in terms of the masses of $_1H^1$ and $_1H^2$, which last are very well known. By measuring the kinetic energy of the emerging electron we can evaluate E of equation 3 and then solve this equation for the mass of $_2He^3$. By going back to process 1 and measuring the kinetic energies of the $_2He^3$ and $_0n^1$ we can evaluate the Q of that equation, which I have already given as 3,170,000 electron volts. We can then use equation 1 to determine the mass of the $_2He^3$ nucleus derived directly from this reaction, provided we have a good independent value of the mass of the neutron. Actually it is more nearly the other way about: we use this equation more for determining the neutron-mass, and we get the preferred value of the mass of $_2He^3$ from the equation describing some other reaction of transmutation in which the masses of the two original nuclei and of the other newborn nucleus are particularly well known. There are in fact so many reactions of transmutation that for many a nucleus the mass can be determined in a half-dozen different ways, and as a rule the concordance is remarkable.

SUMMARY

Now let me summarize. The atom-nucleus is a body comprising nearly the entire mass of the atom. It is distinguished by the features of mass and positive charge, as well as others which in the time available there was no point in mentioning. The positive charge determines the element to which it belongs, the mass determines the isotope. A nucleus is regarded as a cluster of particles of two kinds, the proton which has a charge and the neutron which does not. In making a model for a given nucleus, the number of protons is adjusted to fit the charge, the number of neutrons is adjusted so that when added to the number of protons it gives approximately the right mass. The proton and the neutron are well known as free and independent particles in Nature, and their masses have been measured. The mass of any nucleus, the free proton and neutron alone excepted, is slightly but significantly less than the sum of the masses of the protons and neutrons which make it up. The deficit is the binding want-of-energy of the nucleus, the measure of the tightness with which it is held together. The actual mass is a measure of the energy of the system of protons and neutrons grouped into this nucleus. If two nuclei are driven into contact, and if there is an alternative grouping of their component particles which is of lesser energy than the actual one, then there is a tendency for the particles to go over into the alternative grouping. When this tendency is fulfilled, two newborn nuclei (or sometimes only one) appear in place of the two which originally collided, but they contain just the same basic particles in a new distribution. This is transmutation. Sometimes one of the newborn nuclei has a tendency to emit an electron spontaneously. This is a type of radio-activity, and we call such nuclei by the name of artificial or induced radioactive substances.

Such are the beginnings of nuclear physics. Just how small a beginning I have made, I will close by indicating. One hint I have already given: there are a great many reactions of transmutation, of which I have described no more than two. You have been told of one artificial radioactive substance: actually there are more than 300, and among them is included at least one isotope of every element known. In addition, a great many stable nuclei have been created by transmutation. I am not aware that anyone has lately made an effort to count them all; but it is known that there are nearly 300 kinds of stable nuclei found on this earth, and it is my guess that more than half of them have been reproduced by transmutation. Have any stable nuclei been made which were not previously known? Yes, $_2He^3$ was such a nucleus, and so also was an isotope of oxygen, $_8O^{17}$; but both have since been discovered, very rare but unmistakable. It appears therefore that Nature has done very well in stocking this earth with all possible types of stable nucleus. Perhaps men do not have the privilege of building nuclei which are both unprecedented and immortal; but for mortal beings this may be seemly. Things which are transient are often regarded as more precious than things which are permanent. The nuclear physicist has made enough of a diversity of these transient radioactive nuclei, to give him ample right to style himself a nuclear architect. How precious they may be is something that you will never fully hear, unless you ask the chemists, the biologists, and the physicians to join the physicists in telling you the story.

The Riverside Generating Station

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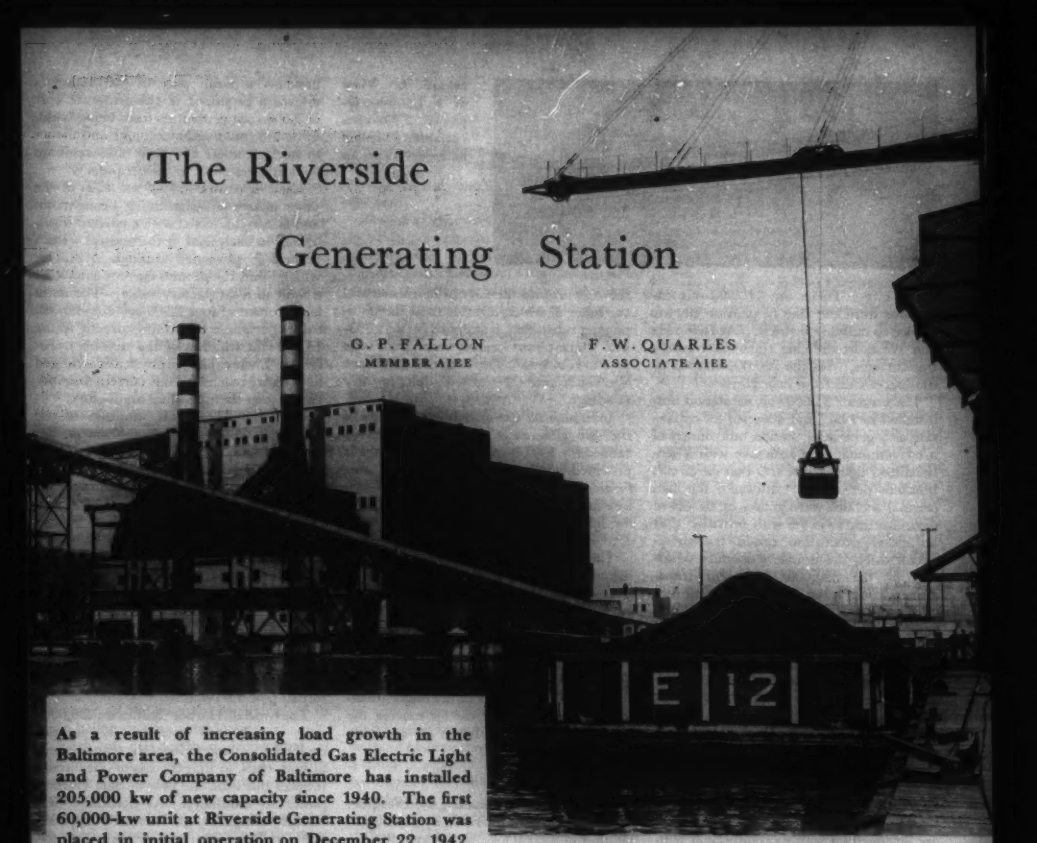

As a result of increasing load growth in the Baltimore area, the Consolidated Gas Electric Light and Power Company of Baltimore has installed 205,000 kw of new capacity since 1940. The first 60,000-kw unit at Riverside Generating Station was placed in initial operation on December 22, 1942, and the second, on April 26, 1944. The two-unit installation is the initial step in the development of a waterfront site convenient to both the transmission facilities and the growing industries.

GROWTH of industrial load in the eastern section of Baltimore and on the north side of the Patapasco River resulted in 1937 in the extension of transmission circuits from Westport and Safe Harbor generating plants to the Riverside property, a tract of land situated on the Patapsco River, southeast of the Municipal Airport, and acquired by the Consolidated Gas Electric Light and Power Company of Baltimore in 1922.

There were in existence at that time two 33,000-volt underground circuits from Westport through Gould Street and Newgate Substations to Riverside. The Safe Harbor circuit took the form of a 220,000-volt transmission line terminating in a 126,000-kva transformer bank stepping down to 33,000 volts at Riverside. In addition to these circuits, two 33,000-volt circuits were run to the Bethlehem Steel Company at Sparrows Point, and a 33,000/4,150 - volt transformer bank was installed to supply local distribution service from Riverside.

In 1940 the steam generating capacity in Baltimore consisted mainly of the Westport and Gould Street plants. With the completion of the installation of a 25,000-kw superposed unit at Westport in 1940, the Westport plant had 125,000 kw of 25-cycle and 65,000 kw of 60-cycle capacity. In 1941 a 60,000-kw condensing unit was put in service at the same location.

The Gould Street plant had 72,000 kw of 60-cycle capacity. In addition, the small standby Pratt Street plant had 20,000 kw of 25-cycle capacity available under certain conditions. As the Pratt Street plant is primarily one of the sources of steam for the district steam-heating system, at times this imposes a limitation on the amount of steam available for driving the 20,000-kw unit.

A completely new steam-electric generation plant was erected at Riverside. The initial installation consisted of a 60,000-kw condensing unit which was placed in service in December 1942. A second unit of the same size was installed and began operation in April 1944. The two Riverside units substantially duplicate the 60,000-kw condensing unit installed at Westport in 1941.

An important element in the company's electric-transmission system is the 110,000-volt "ring" that surrounds Baltimore at a radius of some ten miles. Riverside Station is its eastern terminus, and the western terminus is at the Westport Station; between these stations there are 33,000-volt cables, thus forming a complete circle of 60-cycle transmission around the

Essential substance of a paper presented at a joint meeting of the Maryland Sections of AIEE and American Society of Mechanical Engineers in May 1945.

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Figure 1. View of a 1,500-horsepower 3,600-rpm variable - speed boiler-feed - pump motor

entire city. There are 110,000-volt extensions from the ring to provide electric service to outlying districts. At Riverside and Westport the ring connects, through transformers, with the 220,000-volt transmission circuits from Safe Harbor.

The outdoor 33,000-volt substation bus, installed in 1937, and designed for expansion as a generating station bus consists of a conventional steel structure with a sectionalized double bus and two oil circuit breakers per circuit. Initially, the two original sections were joined by means of disconnecting switches with provision that as added generation raised the short-circuit duty, the double secondary windings of the 220,000/33,000-volt transformers could serve as a reactance tie between the bus sections. Expansion beyond two generators at Riverside will call for additional sections joined to the original bus by means of reactors.

The 220,000-volt line from Safe Harbor is connected directly to the high-voltage windings of the 126,000-kva transformer bank through an air-break switch and single-pole remote-operated disconnecting switches. The transformer bank consists of four single-phase units having a self-cooled rating of 28,000 kva each and an air-blast rating of 42,000 kva each. Windings are arranged for star–star connection with a delta tertiary winding. Each transformer has two separate 33,000-volt windings, and each winding is connected to a separate section of the 33,000-volt bus through oil switches. This arrangement provides reactance between the two bus sections. Each of the transformers, which are of the outdoor oil-filled load-ratio-control type with radiators, is located over a large pit filled with crushed stone and is provided with a permanently piped fire-fighting system having an array of nozzles for fighting transformer fires with water. The pit is provided with an overflow pipe which is in the form of an inverted siphon to remove any water discharged by the system and still contain the oil in case of a transformer tank failure. There are also vertical motor-driven sump pumps for completely draining the pits. The transformers are equipped with the usual nitrogen gas seal with automatic pressure-regulating equipment. The spare transformer is provided with remote-operated disconnecting switches to allow its substitution for any unit in the bank.

Each of the two 110,000-volt circuits leaving Riverside, one of which is part of the ring around the City of Baltimore and the other of which terminates at the Gunpowder substation, is supplied by a 53,333-kva three-phase transformer from the 33,000-volt bus. These transformers are also connected star–star with delta tertiary windings.

Inasmuch as the armature windings of the two generators at Riverside are arranged for 13,800-volt service, each unit is provided with a three-phase auto-transformer having a self-cooled rating of 60,000 kva and an air-blast rating of 80,000 kva for delivering generator power direct to the 33,000-volt busses.

The arrangement of all circuits connecting to the 33,000-volt busses is such that a bus differential-relay protective system can be used for isolating a faulty bus section with a minimum effect on load or power supply.

Adjacent to the switchyard is an assembly house with a permanent track system extending to all six of the major transformers and a transfer car for moving the transformers into the house for assembly or major repairs.

MAIN GENERATORS

Each generator, including the Westport machine, was initially rated by the manufacturer at 50,000 kw, 62,500 kva, for operation at one-half-pound gauge hydrogen pressure and at 50,000 kw, 71,875 kva, for 15-pound gauge hydrogen pressure. It has been demonstrated conclusively in operation that these units are capable of carrying 60,000 kw each, and, consequently, they are rated at this figure. The kilovolt-ampere ratings are unchanged, with corresponding power factors of 96 and 83.3 per cent, respectively. The main generators are of compact construction, as they are designed for operation at 3,600 rpm with hydrogen as the cooling medium. The hydrogen is circulated by fans directly attached to the rotors and is cooled by four coolers mounted in the generator housing. Because of the corrosive nature of the harbor water that is used for cooling, it was necessary to construct the cooler tubes of a copper–nickel alloy. The fins on the tubes, however, are of standard copper construction.

The armatures of both generators are resiliently mounted by means of flexible bars in the same manner as that of the 25,000-kw superposed unit at Westport, which was a pioneer installation of this design. The resilient mounting method prevents a large part of the 120-cycle vibration produced in the armature core of 3,600-rpm generators from being transmitted to building foundations and thence to steel members and parts often resonant or nearly resonant to this frequency.

Each armature has all six leads of the three phases of the winding brought out and is star-connected with a current transformer in each lead to the neutral. Each neutral is grounded through a reactor which limits the ground current caused by a fault to a satisfactory value. The main leads consist of four 2,500,000-circular-mil cables per phase connecting directly to the 13,800-volt winding of the step-up transformer. These cables are physically arranged to equalize reactance and current distribution among the individual conductors.

Only the 33,000-volt windings of the 60,000/80,000-kva-unit transformers are provided with oil circuit breakers. These breakers are located in the 33,000-volt outdoor bus structure and connect the generators directly to the 33,000-volt busses.

The main field is wound with aluminum conductors in order to reduce the amount of mass rotating at high speed and thus diminish the stresses.

MAIN CIRCUIT RELAYS

In general, main power-supply circuits of the Baltimore system are arranged so that the loss of a circuit does not seriously impair power service.

The two Safe Harbor–Baltimore 220,000-volt circuits are operated in parallel on the low-voltage sides of the transformers at both ends, so that the loss of one circuit reduces but little the flow of Safe Harbor power to Baltimore. At Baltimore one circuit terminates at Westport and the other at Riverside, and they are tied together by the 33,000-volt cables which extend from Westport to Gould Street to Riverside and by the 110,000-volt transmission ring which extends from Westport around the city to Riverside.

The 220,000-volt Safe Harbor-to-Riverside line is equipped with high-speed carrier-current relaying which is arranged to cause instantaneous tripping of the oil switches on the low-voltage side of the transformer banks at each end when a fault occurs at any point on the line. The transformers are protected for breakdown with high-speed transformer differential relays which trip the 33,000-volt oil switch and block the carrier-current signals in order to permit relays at Safe Harbor to function and to clear the line at that end.

The two 110,000-volt transformers and their transmission lines are protected by high-speed relays which function instantaneously for phase-to-phase and phase-to-ground faults over a large portion of the lines, with inverse-time overload relays set to co-ordinate with the relaying and fuses at stations supplied from these lines. These transformers also are equipped with differential relays which operate on trans-

former breakdown to trip the 33,000-volt supply breakers and block automatic reclosing.

The 33,000-volt tie cable circuits (three three-phase cables per circuit) to Gould Street and Westport are equipped with special high-speed differential relays which trip the oil circuit breakers of the faulted circuit and indicate which cable of the group of three has failed. In addition, there are inverse-time overcurrent relays which protect against faults between the bus and the cable reactors and which also serve as backup relays.

Sensitive generator differential relays are applied to the 60,000-kw generators, and slightly less sensitive transformer differential relays are applied to the combination of both generator and transformer, thus serving as backup to the generator relays. Either of these relays trips the 33,000-volt generator breakers and corresponding generator field breaker.

AUXILIARY GENERATOR

The decision to pattern the Riverside design after that of the 60,000-kw installation at Westport implied the like use of an auxiliary generator directly connected to the main-generator rotor to act as the normal source of power for certain auxiliaries, the loss of which will promptly shut down the boiler–turbine combination. By a slight modification of the Westport design, the size of the auxiliary generator was increased to 4,000 kw in order for it to carry all the essential auxiliaries of its own boiler–turbine combination.

Each of the auxiliary generators at Riverside has a closed system of air cooling and is rated 4,000 kw, 5,000 kva, at 2,300 volts, 60 cycles. The coolers are of the finned type and have copper–nickel tubes in which harbor water flows from the same source as that feeding the main-generator hydrogen coolers. The auxiliary-generator rotor is coupled to the main-generator rotor so that the voltages of each machine are in phase at zero load.

In starting, the essential auxiliaries receive their power from the station bus through a service transformer, and the auxiliary generator is paralleled immediately after the synchronization of the main unit. In shutting down, the transfer of auxiliary load to the service transformer and the subsequent opening of the auxiliary-generator breaker precedes that of the main-generator breaker.

EXCITERS AND VOLTAGE REGULATORS

The high degree of reliability of auxiliary power furnished by the direct-connected auxiliary generators made feasible the use of low-speed induction-motor-driven exciter sets for the main and auxiliary fields. Each normal exciter set consists of a 500-horsepower 890-rpm induction motor driving a 220-kw main field exciter; a 30-kw auxiliary field exciter; and a $7\frac{1}{2}$-kw pilot exciter which serves the fields of the other two exciters. The station emergency exciter set acts as a spare for the two present units but is somewhat larger in capacity to provide for a moderate increase in unit size for future machines. This exciter consists of a 700-horsepower motor driving a 300-kw main exciter, a 50-kw auxiliary exciter, and a $7\frac{1}{2}$-kw pilot exciter.

An Amplidyne voltage regulator is provided in conjunction with each main field exciter. This device, a generator of special construction driven by a five horsepower motor, is designed to maintain the main-generator voltage at the correct value.

AUXILIARY TRANSFORMERS AND BUSSES

There are two 6,000-kva 34,500/2,400-volt three-phase 60-cycle outdoor-type oil-filled self-cooled transformers for supplying power to the plant auxiliaries from the 33,000-volt bus. One of these connects to the 2,300-volt transfer bus. Normally, this transformer is used only during the starting period, when the auxiliary generator is not at full speed, to furnish power to the busses supplying essential turbine and boiler auxiliaries, or when it is desired to start a motor having a high current demand. For example, the transformer and auxiliary generator are operated in parallel during the starting of the large boiler-feed-pump motors. This transformer also is used as an emergency supply for the plant service bus.

The second transformer normally is used to supply the 2,300-volt plant service bus to which are connected those auxiliaries which may be stopped for a short time without causing much difficulty other than a delay of service. However, it is possible to connect this plant service bus to the transfer bus just described for supplying both types of services under unusual conditions. There are three 440-volt busses supplied from corresponding 2,300-volt busses by means of transformers. Small auxiliaries of each boiler and turbine are supplied from a 440-volt bus connected by a 300-kva transformer bank to the 2,300-volt unit bus which, in turn, is supplied from the auxiliary generator of the associated unit. The 440-volt plant service bus differs from the comparable 2,300-volt bus in that it has two sections, each supplied by a 1,000-kva transformer, and it serves the small auxiliaries.

RELAYING OF STATION AUXILIARIES

The auxiliary generators have differential relays which trip their respective main and field breakers for armature breakdown. They also have inverse-time overcurrent relays and undervoltage relays which trip their main breakers. The tripping of the auxiliary-generator main breaker by any of the relays previously mentioned also automatically closes the tie breaker between the unit bus and the transfer bus which is supplied by a service transformer. If low voltage persists on the unit bus after this operation, a second low-voltage relay trips breakers which shut down the forced- and induced-draft fans, pulverizing mills, and their blowers which are supplied from this bus. This is done not only to protect the motors from extreme low voltage but to minimize chances of fuel explosion in the boiler.

Each of the two 6,000-kva service transformers has inverse-time overcurrent and instantaneous differential-relay protection. The two 1,000-kva and two 300-kva transformers supplying the 440-volt service busses have inverse-time overcurrent relays. Undervoltage on a 440-volt bus causes tripping of the normal supply breaker and closing of the tie breaker to the plant service bus, thus providing restoration of service from another source.

In general, the 2,300-volt plant feeder

Figure 2. East side of the turbine room showing in background 2,300-volt turbine bus and switchgear enclosure and boiler-feed-pump controllers

breakers are supplied with induction-type inverse-time overcurrent relays, while the 440-volt feeder breakers have built-in magnetic overcurrent trip mechanisms with oil-film time-delay attachments.

2,300-VOLT AND 440-VOLT CIRCUIT BREAKERS

All circuit breakers on the 2,300-volt busses have 150,000-kva rupturing capacity and are of the air-break solenoid-operated trip-free type, housed in individual steel cubicles which are arranged in groups. The circuit breakers attached to the 440-volt busses have an interrupting capacity of 50,000 amperes and are of the air-break type, housed in cubicles and protected by interlocks.

ELECTRIC PRECIPITATORS

In each of the two flue gas streams leaving each boiler there is a precipitator for the electrostatic removal of flue dust. The electrodes of each precipitator are supplied with high-voltage rectified current obtained from a 75,000-volt transformer and from a synchronous motor-operated full-wave mechanical rectifier (spark-gap unit).

Each precipitator has inlet and outlet electrodes so connected that one receives the positive half wave and the other the negative half wave of the rectified power. The precipitators are supplied from the 440-volt plant service bus and are equipped with a spare transformer and rectifier unit which can be substituted for any of the normally operating units.

MOTORS AND CONTROL

In general, motors of 60-horsepower capacity and larger are supplied from 2,300-volt circuits. Those between 60 and 1 horsepower are supplied from 440-volt circuits and those below one horsepower from the 120/208-volt lighting circuits. The coal-handling equipment deviates from this plan in that 2,300-volt service is delivered to the site and stepped down for the simple reason that it is more economical to use 440-volt controllers.

Wherever feasible, rugged full-voltage-starting sleeve-bearing squirrel-cage induction motors have been used to drive auxiliaries. This policy extends up to and includes the 1,500-horsepower dual-drive emergency boiler-feed pump.

In addition to the 1,500-horsepower emergency boiler-feed pump, 2,300-volt squirrel-cage motors are used in the following sizes: 250 horsepower for forced-draft fans, 75 horsepower for pulverizer mills, 60 horsepower for primary-air fans, 250 horsepower for vertical circulator pumps, 700 and 500 horsepower for exciters, 200 horsepower for ash-sluice pumps and 100 horsepower for air compressors.

Wound-rotor motors are used in some applications to provide the adjustment of pump and fan speed necessary for the accurate control of a large unit installation without encountering the mechanical difficulties arising from various types of variable-speed couplings, vane controls, throttling means, and the like. These wound-rotor motors vary in size from 1,500 horsepower on boiler-feed pumps down through 400 horsepower on induced-draft fans, to 150 horsepower condensate-pump motors, and to miscellaneous applications as small as 25 horsepower.

The variable-speed motors driving the normal boiler-feed pumps are believed to be the first wound-rotor motors built in the United States for as large a capacity as 1,500 horsepower at 3,600 rpm. They are used mainly to reduce the high pressure drops across the boiler-feed-control valves and the resulting maintenance costs and outages, both of which would be encountered by the use of constant-speed motors. There is also less wear on the pump and slightly better power economy by the use of the variable-speed drive. The controllers for these motors are the drum type with pilot-motor-driven cams which provide 19 balanced operating points. Because of the importance of the service, these controllers have extra direct-connected pilot motors to substitute for the regular motors in case of need.

Each of the two induced-draft fans per boiler is driven by a wound-rotor motor having a capacity of 400 horsepower at full speed of 885 rpm. The controllers for these motors are also of the drum type with pilot-motor-driven cams which provide 13 balanced points, and normally the two controllers are mechanically connected to provide simultaneous operation. Each controller has its own pilot motor for individual use, if desired.

The two condensate pumps per unit are rated at 150 horsepower for full speed of 1,165 rpm and are controlled by hand-operated drums with cams giving 13 balanced points.

The control of the motors of the coal-conveying equipment is interlocked to prevent coal from piling up on receiving equipment when the equipment is not running. As there are four modes of operation of this equipment, a four-position sequence-selector switch is provided to set up adequate circuit interlocking. The control of the motors of the fans and mills of the boilers likewise is interlocked to protect against fuel explosions or discharge of hot gases into the boiler room.

D-C SERVICE AND BATTERY

The control power for operation of circuit breakers, motor-operated valves, and other devices of the essential type is obtained from a 250-volt d-c bus on which floats a 400-ampere-hour storage battery. The battery is center-tapped and upon failure of the a-c lighting supply serves as a source of power for the emergency or essential lighting circuits. Because of the center tapping, the a-c motor-driven battery-charging set is of the two-unit type having two 20-kw 125-volt shunt-wound generators with voltage maintained at the correct value by an electronic voltage regulator.

The battery booster set also has two shunt-wound generators for interposition between the bus and the battery, so that the bus voltage may be held at 250 volts while the battery is being charged. In case of abnormal lowering of bus voltage while the battery is being charged by the booster, the battery breaker closes and the booster breaker opens, thus connecting the battery directly to the bus.

The turbine-room crane, elevator, and coal-belt magnetic pulley are supplied with 250-volt d-c power from a 75-kw motor generator set, with provision made for supplying this service from the emergency main exciter in case of an outage of this set.

PLANT-LIGHTING CIRCUITS

Most of the main lighting circuits which are 120 volt 60 cycle are supplied through single-phase 2,400-to-120-volt transformers connected to the 2,300-volt three-phase service bus. The secondary windings of these transformers are star-connected with grounded neutral and provide 208-volt three-phase power for miscellaneous fractional-horsepower motors. Emergency lighting circuits normally are supplied by 120-volt a-c power, and, when a deficiency of alternating voltage occurs, they are transferred to the battery by an automatic-change-over panel.

COMMUNICATION FACILITIES

Two main communication systems are provided at important operating locations in the boiler house and turbine room. The first is that of regular Bell System automatic dial telephones connected to a local satellite board which, in turn, is connected to the company's main board by trunk lines. The other system of communication is entirely local, being that of telautographs arranged so that all stations write in unison and any station can act as a sender. Both of these communication systems reach the switchboard operator in the control house, and, in addition, he has available a private line to a third separate communication system connecting with the electric load dispatcher.

CONCLUSION

The design of the electrical facilities at Riverside was carried out by the electrical engineers department of the company with the co-operation of the operating departments, and the aim throughout has been to obtain a high degree of reliability, together with low operating and maintenance expenditures, with proper consideration being given to fixed costs. The exceptional reliability attained is well demonstrated by the fact that for the year 1944 the generator outage factor for unit 1 was 0.21 per cent and for unit 2 was 0.50 per cent. Unit 1 was operated for more than 90 per cent of the hours in the year 1944, and unit 2 was operated for nearly 94 per cent of the hours remaining in the year after its installation.

Application of Electronics in the Electric Power Industry

C. F. WAGNER
FELLOW AIEE

The role of the mercury-arc rectifier in power conversion, the use of ignitrons as electronic exciters, and the diversified applications of the precipitator are discussed at length in this article.

THE APPLICATION of electronics in the electric-power industry has become wide-spread and this expansion has resulted in greater power transmission and more flexible operation of power systems. Electronic developments not only have helped the industry meet wartime demands but also have assured it a future market for its increased power and efficiency.

METAL-TANK RECTIFIERS

Many contributing causes for the expanding uses of electronic devices in the power field can be listed in a survey on electronic applications. The introduction of the steel tank to mercury-pool-type rectifiers was probably the greatest contributing factor toward bringing the mercury-arc type rectifier into the power conversion field. Its acceptance is due to its low maintenance and low outage factor. Its efficiency, particularly at light loads and in the higher-voltage classes, shows to advantage over the rotating types of converters. Contrasted with rotating machines, metal-tank rectifiers produce less vibration and less noise. A survey of the period from 1920 to 1940 shows that approximately 500,000 kw of mercury-arc rectifiers were installed in the United States in the transportation, electrochemical, and power fields. These consisted largely of multianode tank type of construction. During this time, work was done on a single-anode tank and the first rectifier of this type, known as the ignitron, was introduced commercially in 1937. The advantages of the single-anode rectifier compared with the multianode rectifier, soon made it the most popular type of device. In the period from 1940 to the present time approximately 3,800,000 kw of all types were installed, largely in the electrochemical field in Canada and the United States. Of these, 3,200,000 kw were ignitrons.

Today the mercury-arc rectifier has practically displaced the rotary converter in new installations requiring conversion. In addition to the electrochemical field, it also finds application in such industries as mining, railway, steel, and paper, and also in the power field where a small source of direct current is required in the process of converting d-c distribution systems to a-c networks.

D-C TRANSMISSION

In many fields the word *electronics* has been the watchword for unrestrained visionary engineering. In no branch has a little engineering development unleashed such optimistic forecasts as in d-c transmission. This state of mind created a feeling of uncertainty in the industry concerning all forms of transmission of power.

D-c transmission consists essentially of generation at alternating current, transformation from generation to transmission voltage, rectification to high-voltage direct current, transmission at high-voltage direct current, inversion at the receiving end to high-voltage alternating current, transformation again to low-voltage alternating current, from which it can be distributed. The two advantages that are usually claimed for d-c transmission are first, the removal of the stability problem and second, the more economical utilization of the line. Considering the first point, for d-c transmission, power is transmitted by voltage drop and the stability problem it practically eliminated. As to economy is is frequently assumed that for a given line construction and insulation, the d-c voltage across a string of insulators at which the line can operate is equal to the crest value of the corresponding line to neutral voltage of the a-c line. On this basis the d-c line can transmit at least 40 per cent more power than the a-c line for the same loss. Actually, the problem is not so simple. For voltages at which d-c transmission might be attractive, the line insulation is determined largely by considerations arising from the surges resulting from lightning. Under normal conditions, the distribution of voltage along a string of insulators for direct current may be more or less uniform than for alternating current, depending upon the amount and distribution

Figure 1. Westinghouse Electric Corporation 5,000-kw electronic frequency changer

External view showing transformers, reactors, and switchgear

Essential substance of an address delivered before the AIEE Montreal Section, November 10, 1944.

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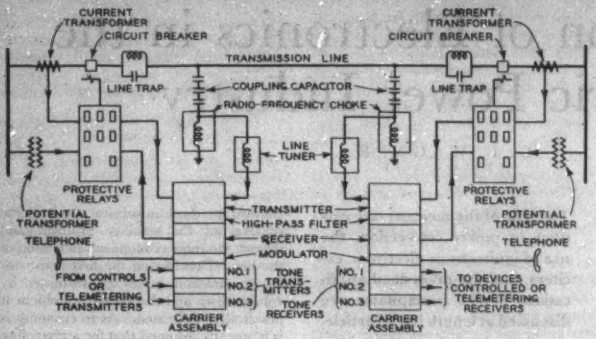

Figure 2. Schematic diagram of carrier-current system

of dirt upon the insulators. For alternating current not all faults develop into power arcs as would be the case for direct current. Until operating experience is collected on some of these questions, a true comparison is not possible.

D-c transmission requires more equipment than a-c transmission—equipment less tried by operational experience. If the equipment were fully developed, the balancing point between the cost of a-c and d-c transmission from present estimates would be somewhere in excess of 300 miles and blocks of power in excess of 300,000 kw. Power of this magnitude requires rectifiers and inverters capable of operating at voltages of the order of 200,000 volts. Tubes of about 15,000 to 20,000 volts operating at about 1,000 kw each are available today. Several hundred of such tubes, connected in series and multiple, would be required at each end of the line. The cost of conversion equipment almost limits the system to straight-away transmission without tap points. Reactive kilovolt-amperes cannot be transmitted but must be supplied at the receiving end, which may require the installation of additional synchronous condenser capacity.

Because of the higher cost per mile of cable, the benefits of high-voltage d-c transmission are more pronounced in cable transmission than for open lines. On account of the marked reduction in dielectric loss, a given cable can operate at much higher direct than alternating voltage. These two factors justify consideration of d-c transmission for much shorter cable distances than for open lines. Where a tie line is intended to connect systems of different frequencies, the added advantage of frequency conversion justifies d-c transmission for shorter distances, lower voltage and lower power for either open lines or cables.

As improvements are made that are conducive to d-c transmission other improvements are simultaneously being made in a-c transmission. Thus, with improvements in high-speed clearing of faults and reclosing, the transient limits are approaching the steady-state limits. Series capacitors can also be expected to increase transient stability limits. Who can tell what further developments lie on the horizon? Thus, the competitive situation for d-c transmission is continually becoming more severe.

FREQUENCY CONVERTERS

Frequency converters are similar to d-c transmission systems except that the transmission line is omitted. They may be used to provide a flexible tie between two systems. The frequency of one system can change over wide limits without affecting the other. This advantage is particularly applicable to tie 60-cycle utility systems with 25-cycle steel-mill systems. The latter have very high sudden demands for power and if connected rigidly to the 60-cycle system transmits the demand to it. Figure 1 shows the external view of a laboratory 5,000-kw set. The experience obtained with electronic frequency changers should be of enormous value in providing the experimental foundation for d-c transmission. With this information as a background it will be possible to speak with definite and less imaginative engineering knowledge than has been the case in the past.

EXCITERS

Exciters have had an availability factor comparable to that of the main machine. However, since it is not the principal element in the unit, exciter troubles have been emphasized beyond their real importance. This is particularly true of direct-connected exciters, maintenance of which requires shutdown of the whole unit. This philosophy has engendered sympathetic consideration of the electronic exciter as a means of supplying excitation. Being independent of the main unit any servicing that might be required can be done without shutting down the whole unit.

Ignitrons with their vast background of experience are being applied as electronic exciters. The time lag of the rotating exciter is eliminated because the voltage reaches the ceiling value within a quarter cycle, the only lag being that due to the regulator. With this type of excitation special consideration must be given to the voltage supply. In one case this is taken from the same supply as the auxiliaries. Consideration has also been given to providing a separate synchronous machine on the shaft of the machine. A third proposal, one unit of which is being supplied on a particular job, is to connect the rectifier across the terminals of the main machine. In this case any drop in system voltage, such as might result from a fault, produces a drop in voltage applied to the main field winding and at an instant when it is most undesirable. To obviate this difficulty a series compensator is placed in each phase next to the neutral which increases the rectifier voltage at times of a system short circuit. This unit has been tested in the laboratory and will be given more extensive tests in supplying the excitation to one of the units in the Westinghouse high-power laboratory. By this means the essential conditions met in practice may be simulated. The electronic excitation system costs appreciably more than a direct-connected exciter or a separate motor generator set. The extra cost must be justified by increased reliability or higher response.

Inquiries have also been made on

Table I

$\frac{\Delta V}{I}$	J_0	J_1	J_2	J_3	J_4	J_5	J_6	J_7	J_8	J_9	J_{10}	J_{11}	J_{12}
0	1												
0.2	0.99	0.10	0.005										
0.5	0.94	0.24	0.03										
1.0	0.77	0.44	0.11	0.02	0.002								
2.0	0.22	0.58	0.35	0.13	0.03	0.01							
5.0	−0.18	−0.33	0.05	0.36	0.39	0.26	0.131	0.05	0.02	0.06	0.15	0.04	0.08
10.0	−0.25	0.04	0.25	0.06	−0.22	−0.23	−0.01	0.22	0.32	0.29	0.21	0.12	0.09

means of eliminating pilot exciters. Two of the proposals to accomplish this end are (1) improvement in stability of the direct-connected main exciter and (2) replacement of the pilot exciter by a permanent magnet synchronous machine with a rectox rectifier to supply the direct current.

POWER-LINE CARRIER

Because of its great versatility, power-line-carrier equipment is attaining greater and greater acceptance by utilities. While

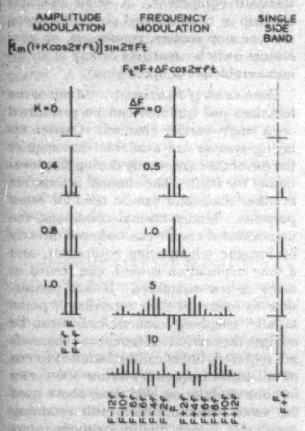

Figure 3. Distribution of side bands

it was originally introduced for communication purposes, it has expanded now to include relaying, telemetering, supervisory control, and load control. Figure 2 shows a schematic diagram of a complete system adaptable to several functions. Standard rack-mounted carrier components are now available from which combinations can be selected to perform exactly the functions desired with a minimum of equipment and a maximum of convenience and flexibility.

Power-line carrier is a high-frequency (50 to 150 kilocycles) current that is fed into the power line through coupling capacitors which to the lower power frequency are essentially insulators. When desired, the loss of carrier-frequency energy can be minimized by means of line traps, that look much like current-limiting reactors but which can be tuned to offer high impedance to carrier currents. Line traps are used principally when the carrier is used for relaying purposes to prevent short-circuiting of the carrier for faults outside of the section of line being protected.

Three types of power-line carrier are used today; namely, amplitude modulation, frequency modulation, and single side-band or suppressed carrier. In amplitude modulation the amplitude of the carrier current is modulated in response to the voice fluctuations. Since these fluctuations can be resolved into frequencies within the speech range of 3,000 cycles per second, the performance for any one audio frequency can be represented by the expression

$$I_t = I_m[(1 + K\cos 2\pi ft)]\sin 2\pi Ft \qquad (1)$$

in which F is the carrier frequency, f the audio frequency, I_m the amplitude of the unmodulated carrier, and KI_m the amplitude of the audio fluctuations. The expression in brackets can be viewed as the amplitude of the carrier current, which is, of course, varying at audio frequency. This expression can be transformed to

$$I_t = I_m \sin 2\pi Ft + 0.5I_m \sin 2\pi(F-f)t + 0.5KI_m \sin 2\pi(F+f)t \qquad (2)$$

The second term is the lower side band at frequency $(F-f)$, lower than the carrier by the audio frequency and the third term is the upper side band, at frequency $(F+f)$, greater than carrier by the audio frequency. Figure 3 shows how the side bands vary as the modulation increases for a given audio frequency.

In frequency modulation systems the instantaneous value of the carrier frequency changes in response to the audio modulation. The transmitted wave can be regarded as the projection of a vector of constant amplitude that rotates with non-uniform speed—the audio frequencies being superposed upon the constant-carrier frequency. If ΔF is the increment in transmitted frequency then the instantaneous angular velocity or speed of this vector (for a given audio frequency) is

$$2\pi F_i = 2\pi F + 2\Delta F \cos 2\pi ft \qquad (3)$$

the instantaneous position of the vector (or phase position) is

$$\alpha = \int^t (2\pi F + 2\pi\Delta F \cos 2\pi ft)dt = 2\pi Ft + \frac{\Delta F}{f}\sin 2\pi ft \qquad (4)$$

Then the instantaneous value of the transmitted current is

$$I_f = I_m \sin \alpha = I_m \sin\left[2\pi Ft + \frac{\Delta F}{f}\sin 2\pi ft\right] \qquad (5)$$

Figure 4. Transmission circuit

Breaker at A must discriminate between fault at F_1 and F_2

This expression can be expanded into a spectrum distribution.

$$I_f = I_m\left\{J_0\left(\frac{\Delta F}{f}\right)\sin 2\pi Ft + J_1\left(\frac{\Delta F}{f}\right)[\sin 2\pi(F+f)t - \sin 2\pi(F-f)t] + J_2\left(\frac{\Delta F}{f}\right)[\sin 2\pi(F+2f)t + \sin 2\pi(F-2f)t] + J_3\left(\frac{\Delta F}{f}\right)[\sin 2\pi(F+3f)t - \sin 2\pi(F-3f)t] + \ldots\right\} \qquad (6)$$

Thus it can be seen that the varying-frequency, constant-amplitude wave consists of one component of carrier frequency and an infinite number of side bands. The magnitudes of the carrier wave and side bands are dependent upon the ratio of the increment in carrier frequency to the audio frequency. For a given audio frequency, the side bands change as the intensity of the sound producing the effect increases (or the equivalent, as $\frac{\Delta F}{f}$ increases). Table I shows this variation.

Figure 3 shows how, for a given audio frequency, the side bands change as the intensity of the sound producing the effect increases (or the equivalent, as $\frac{\Delta F}{f}$ increases.)

In single-side-band carrier both the carrier wave and one of the side bands are suppressed and only the remaining side band is transmitted. At the receiving end the transmitted side band is recombined with a locally generated reference carrier to reproduce the original signal. By this scheme it is sufficient to transmit only one intelligence-bearing side band. It differs from both amplitude modulation and frequency modulation in that when no intelligence is being transmitted there is likewise no energy being transmitted. The transmitted side band varies with the intensity of the signal for a given audio frequency.

In comparing these different types of carrier, two principal factors should be considered; namely, the crowding of the carrier spectrum and the effect of interference. By its very nature frequency modulation covers a wide frequency spectrum. In the wide-band system used in frequency-modulation broadcasting this is no particular disadvantage because it is used only in the high-frequency range. Under these conditions a high signal-to-noise ratio is obtained. For carrier work the total available range of frequency is

only 50 to 150 kilocycles and thus the same gains are not attainable. One is restricted to values of $\frac{\Delta F}{f}$ of about 1.0 for an audio frequency of 3,000 cycles and while some gain in signal-to-noise ratio is obtained the frequency band is also increased. With single side band on the other hand very considerable gain is obtained in signal-to-noise ratio without the attendant increase in frequency band width of either amplitude modulation or frequency modulation. For most cases amplitude-modulation schemes are satisfactory but for systems where spectrum crowding is a problem or on long lines where attenuation is high, single side band is the answer. This is of particular value when large numbers of communication channels are required since it requires a smaller portion of the carrier spectrum for each channel.

Communication. Because of the ease with which carrier communication can be accomplished over long distances, it is ideally suited for co-ordinating the operations of remotely located points in extensive systems and can be used for dispatching services and for conducting normal and emergency operations. The equipment available practically duplicates the service obtainable in automatic telephone exchanges. Due to the more substantial construction justified for power lines than for telephone lines, communication by carrier is less likely to be interrupted by natural causes. Communication is usually maintained even though a fault occurs on the transmission line. Particularly for long distances, carrier represents a real saving as compared to separate cables. In some systems a single carrier channel is used to carry on conversation both ways. The function of transferring from transmission to receiving in the "push-to-talk" system is done manually. However, this task can be done automatically by means of an electronic transfer unit. The two-frequency or duplex system is often used where direct communication is required between two points only. In this system speech in one direction is transmitted at one frequency while speech in the other direction is transmitted at another frequency. Both communications can be carried on simultaneously, making the transfer from transmission to reception unnecessary. The duplex system lends itself for carrying into a private-branch-exchange board at either end to serve as a link in a more extensive communication system.

Relaying. Rapid clearing of faults on transmission lines is desirable because it promotes stability of the system, permits faster reclosing, results in less damage to equipment from arcing, and decreases the probability of more than one phase becoming involved in the fault. Carrier-pilot protection offers a medium by which this can be done. Referring to Figure 4, it is difficult for the relays controlling breaker *a* to discriminate between a fault at F_1 and F_2 close to bus *B*. Naturally, breaker *a* should open for a fault at F_1 but not for a fault at F_2. Either sufficient lag must be introduced into the operation of *a* to permit the proper breaker at bus *B* to function and thus change the response quantity at *a* or additional information must be transmitted back to *a* by carrier to permit discrimination. For all faults outside of the section under consideration a blocking signal is transmitted back to *a* by carrier that prevents tripping of that breaker. For faults within the section no signal is transmitted and *a* opens almost instantaneously. By this system simultaneous tripping of both breakers at the ends of the faulted section and consequent clearing of the fault can be achieved in from one to three cycles.

Telemetering and Supervisory Control. Telemetering is the indicating or recording of a quantity at a location remote from the point at which the quantity exists. In power systems the quantity most frequently telemetered is kilowatts, although other quantities, such as voltage, phase angle, reactive power, hot-spot temperature and tap-changer positions can be similarly recorded. Thus, any desired quantity can be brought to a central location for the use of a load dispatcher. All the information is at his disposal for operation of the system. Telemetering schemes or their equivalent can also be used in conjunction with automatic load-control equipment. With carrier supervisory control remote substations can be controlled by standard equipment. A single operator can trip or close selected circuit breakers, start or stop motors, condensers, or generators, switch capacitors or any of an innumberable set of operations.

Combination of Functions. Many of the functions just outlined can be performed on a single carrier channel. Carrier relaying systems are available that require the use of the carrier only during the duration of the fault. The channel is thus free at other times and can be used for other purposes. Under normal conditions, the unmodulated carrier can be keyed directly by impulse telemetering equipment, and if tone modulation is used, can record as many as ten quantities. If it is permissible to interrupt their recording, "push-to-talk" telephone communication can be cut into the carrier. If fewer tone channels are required, filters can be installed to cut off all audio frequencies below 500 cycles for tone modulation, and those above used for voice communication, still retaining acceptable speech quality, without interruption to the tone channels below 500 cycles which can provide four tones. With tone modulation, all the tones can be used simultaneously.

Figure 5. A charging unit (right) and a collecting unit (left) of a Precipitron

ELECTROSTATIC PRECIPITATION

Electrostatic precipitation has long been recognized as the outstanding means of cleaning fine particles from a gas. For years the Cottrell system has been used for the reclamation of flue dust in smelters. In this system alternating voltage of values as high as 100,000 volts is rectified by means of rotating electrodes. The negative terminal of the rectifier is connected to a heavy wire between vertical metal plates spaced 10 or 12 inches apart. The dust-laden air is passed between these electrodes. The dust particles receive a negative charge from the corona and are deposited against the positive plates. This system has not come into use for ventilating systems because the high-voltage corona discharge generates ozone and oxides of nitrogen which are toxic for human consumption. In addition, the power to maintain a continuous discharge in the large spaces utilized by this method requires bulky and expensive transforming and mechanical rectifying equipment.

A new type of precipitator appeared in 1937, a form of which is known as the Precipitron. In this device the function of ionization and precipitation is divorced.

The air is made to pass first between an ionizing space and then through a precipitating space. In the ionizing space a $7\frac{1}{4}$-mil tungsten wire is placed between parallel tubes. The negative terminal of a 13,000-volt d-c supply provided by a power pack is connected to the ionizing wire. The combined use of a lower voltage and positive potential to the ionizing wire results in the production of a negligible amount of toxic gases which thus permits the use of this system for ventilation and air conditioning. In passing through the ionizing space the dust particles collect positive charges which in passing through the precipitating zone cause the particles to be deposited on the negative plates. A source of 6,000 volts direct current, again supplied by a power pack, is used for the precipitating function. The resolution of the two functions by the two-stage precipitator permits utilization of the most efficient voltages for the respective purposes. Figure 5 shows on the right-hand side the charging unit and on the left-hand side a collecting unit. The air flow is from right to left in this figure.

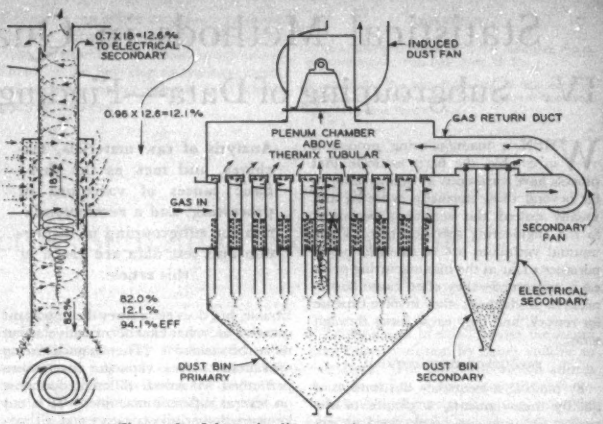

Figure 6. Schematic diagram of duplex collector

APPLICATIONS OF THE PRECIPITRON

The Precipitron has many diversified applications in the domestic, commercial, industrial and central-station fields. The domestic and commercial applications have been of necessity curtailed during the war but the industrial applications have been expanding rapidly. A pilot application in central-station fields is in operation and will provide operating experience valuable to expansion after the war.

The domestic field is one of the most promising. Plans are underway to provide air cleaning for homes. The results obtained from installations in homes in the Pittsburgh area have been very gratifying particularly with regard to maintenance of household furnishings and as a boon to those suffering from hay fever. While the consumption of a particular unit is not large, in the aggregate the load is well worth while particularly as the load factor is excellent. A single unit will add an annual power consumption of about 300 kilowatt hours at 100 per cent load factor. As the present average home power consumption is about 1,000 kilowatt-hours per year, this represents an increase of 30 per cent.

The central-station engineers are interested in this device as a potential load builder.

Many interesting applications of the Precipitron in the industrial field during the war have been recorded. In some plants the oil mist produced by high-speed grinders became so serious that the condensate dripped from the walls and pipes. This led to premature electrical insulation failures and was a health and fire hazard. Precipitating the oil mist at its source not only eliminates this objection but also recovers the oil for reuse. Precipitrons also have been applied for cleaning the air for manufacture, assembly and inspection of aircraft engine parts, optical lenses and instruments, and many other precision products.

Another important application of the Precipitron is its use to clean the ventilating air of large rotating electric machines. A large number of installations have been made in the steel industry for cleaning the ventilating air for mill-drive motors, motor-generator sets and control rooms. Installations have also been made in the central-station field for synchronous condensers, switching rooms and general-purpose ventilation. Recently the Precipitron has been applied to clean the air in the closed recirculating systems of large d-c motors and generators. In this instance, the purpose is to collect the carbon dust borne from brushes to the commutator. The carbon dust is thus prevented from getting into the windings and this condition greatly extends the time between overhauls.

An application of great potentiality in the central-station field is the precipitation of fly ash in stacks. As a result of the researches of the Prat-Daniel Corporation and the Westinghouse Electric Corporation a duplex unit[1] consisting of a mechanical precipitator and an electrical precipitator has been developed. A pilot installation has been installed at the Huntley station of the Buffalo–Niagara Electric Corporation. This unit is intended to handle one quarter of the 900,000 pound per hour generating unit. The general arrangement of the duplex unit is shown on the right-hand side of Figure 6.

The general operation best can be expressed by considering in detail the functioning of a single unit of the mechanical collector which is shown on the left-hand side of Figure 6. The flue gas enters the periphery of the separator and is given a high rotative velocity or cyclonic effect. The heavier particles strike the wall of the tube and drop to the bottom of the primary dust bin. The flue gas then rises through the tube with a continued vortex action. The greater portion of the remaining dust is skimmed off through the upper annular slot to the electrical precipitator, the inner volume of the gas being carried off to the stack. Tests have shown that the efficiency of the Thermix tubular collector is about 80 per cent so that this portion of the dust content drops into the dust bin primary and the rest of the dust rises through the upper portion of the tube. If it is assumed that the collector at the top catches three quarters of the remaining dust then approximately 15 per cent of the original dust content is drained off to the electrical precipitator. The efficiency of the Precipitron for the smaller particles which still remain is in the order of 96 per cent. Thus, nearly all of the dust going to the Precipitron is collected in the dust bin secondary. The over-all efficiency of collection is thus approximately 95 per cent of the original dust content.

MISCELLANEOUS

Many other applications might be cited; for example, the control of a d-c machine from an a-c source, various forms of lighting—the fluorescent lamp, the cathode-ray oscillograph, used to great advantage in impulse testing, and which has been responsible for the great advances in our knowledge of insulation coordination work, cable-testing outfits and a host of other interesting devices.

REFERENCE

1. The Mechanical-Electrical Dust Collector, *Power Plant Engineering*, December 1944, page 190.

Statistical Methods in Quality Control

IV. Subgrouping of Data—Finding Causes of Trouble

Analysis of raw materials, machines, and men as the three basic causes of variations in processing, and a recommendation for subgrouping of inspection and test data are given in this article.

WHEN a manufacturing process is in trouble, the parts made in that process have variations in quality that go far beyond those normally expected and usually exceed the variations permitted in the engineering specifications. These unusual variations are of immediate importance so far as the manufacturing process is concerned—they often cause bottlenecks in production; they involve expense for rework, and they cause losses through scrap.

FREQUENCY DISTRIBUTION

By plotting a frequency distribution of quality measurements, a picture of the present situation can be obtained at any time. But often the verdict of the frequency

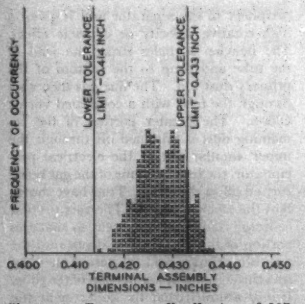

Figure 1. Frequency distribution of 307 capacitor-cover measurements taken from all machines.

distribution is that "something must be done to improve the process."

The frequency distribution shown in Figure 1 indicates the over-all terminal assembly dimensions as measured on 307 capacitor covers. On this job, the upper and lower engineering tolerance limits are 0.433 inches and 0.414 inches, respectively; these are indicated by vertical lines in Figure 1. The verdict of this particular frequency distribution is clear. Out of the 307 capacitor covers 29 had terminal assembly dimensions which exceeded the upper tolerance limit and thus 9.4 per cent of the covers were defective. Evidently, there is room for improvement in this process. The frequency distribution of 307 capacitor covers shows the extent of trouble, but does not answer the important question of "what kind of corrective action must be taken?" The manufacturing operations on these capacitor covers were performed by several different operators on several different machines. It is not known whether all operators and all machines are contributing to this trouble or whether it is "localized."

CAUSES OF PROCESS VARIATIONS

One of the most effective ways of tracking down trouble comes through analysis

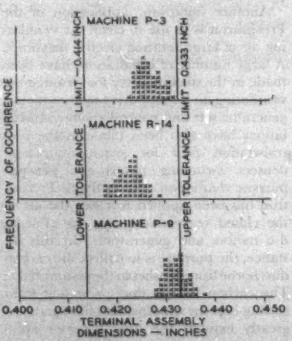

Figure 2. Frequency distribution of capacitor-cover measurements taken from three different machines.

of the effect of possible sources of unusual process variations. The three basic causes of variations in processing are raw materials, machines, and men. These causes may act independently or in unison as to their effect at given stages in production. To find out whether materials, machines, or men are causing the immediate process trouble, we must break down our data into subgroups.

On the capacitor covers, materials were found to come from a common source and to be of controlled quality. The remaining effect of machines and operators was a composite one and, therefore, had to be studied as a whole. As a first step, 50 covers were taken from each machine and plotted against the tolerance limits in the form of frequency distributions. Figure 2 shows typical frequency distributions from three different machines.

Each of these machines has a fairly narrow range for the spread of 50 measurements, but the average dimensions are greatly different. Machines *P*-3 and *R*-14 are making 100 per cent good parts; on the other hand, 24 per cent of the covers produced on machine *P*-9 are defective. Analysis of these subgroups seems to indicate that the machines are in good shape and that operators are doing good work,

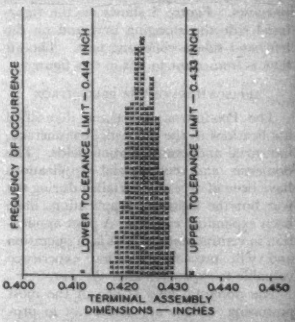

Figure 3. Frequency distribution of 342 capacitor-cover measurements taken from all machines.

but that the differences between machines as to quality are due either to setup or to drift of the dimension during machine use. This called for another study.

RESULTS OF CHECKING

By taking successive checks on the same machine, it was found that:

(1) A given machine will operate at the setup dimension for a fairly long period.

(2) Substantial differences exist between the machines immediately after setup.

This later investigation clearly indicated that the setups were the principal cause of trouble. Action was taken. The nominal dimension of 0.424 inch was selected as a goal for each setup; the setup men were instructed to work as closely as possible to the nominal dimension.

Results showed up immediately in the form of closer adherence of individual covers to the drawing specifications. The overall-spread of measurements decreased as shown in Figure 3. The average measurement for 342 covers in this set was close

One of a series of articles prepared in the AIEE subcommittee on educational activities and sponsored by the AIEE subcommittee on statistical methods.

Personnel of the AIEE subcommittee on educational activities: J. Mansale, H. F. Dodge, A. I. Peterson, and R. E. Wareham.

to the nominal of 0.424 inch and only two pieces fell outside tolerance limits.

Rational subgrouping of inspection and test data to show possible causes of trouble in processing is well worth while. Often, it gives a direct clue as to the real source of trouble; on other occasions, it shows that one variable or another is not the cause of trouble. Rational subgrouping should be the first step in tracking down and locating trouble existing in a manufacturing process.

REFERENCES

1. American War Standard Z 1.3, American Standards Association, 1942, New York, N. Y.

2. Economic Control of Quality of Manufactured Products, W. A. Shewhart, D. Van Nostrand Company, Inc., 1931, New York, N. Y.

Silent Electric Signaling and Control

A new design of mercury switch in which the tube containing the mercury does not move and the make-and-break action is magnetically controlled, has been developed by the Sordoviso Switchgear, Ltd., London, England, according to information supplied by A. G. Whyte through the British Information Service, New York, N. Y.

Earlier designs of mercury switch depended upon the tilting of a tube for the make-and-break action.

This appliance is a glass container with three electrodes, one at the top, one at the bottom, and the third at the side. Mercury partly fills the tube and on it floats an iron armature containing a ball which acts as a valve. When the switch is in the normal position the mercury flows freely into the armature and closes the circuit between the top and bottom electrodes. When, however, the armature is drawn down by the magnetic attraction of an external solenoid, the ball valve closes and the mercury, being thus prevented from flowing into the armature, is forced upwards outside the armature and makes contact with the electrode at the side. As soon as the solenoid is de-energized the reverse action takes place and contact between the top and bottom electrodes is restored. As the tube is filled—apart from the mercury—with nonoxidizing gas, any arc formed at the contacts is quickly and effectively quenched. The electrodes are made of a special alloy with a coefficient of expansion which ensures perfect sealing where they pass through the glass of the tube, and the switches are carefully tested for long periods to ensure no gas leakage.

A time element is introduced by providing in the armature a slot which acts as a by-pass when the ball valve is closed. With the armature in the down position the mercury outside it percolates slowly throught the slot, and eventually makes contact with the top electrode even though the solenoid is in action and keeps the armature down. By the same action the contact with the side electrode may be either broken or may remain closed according to the amount of mercury in the switch. The time interval can be regulated within close limits by adjusting the size of the slot. An important detail of this type of automatic switch is that the movement of the valve keeps the slot clean, so that the mercury always flows freely.

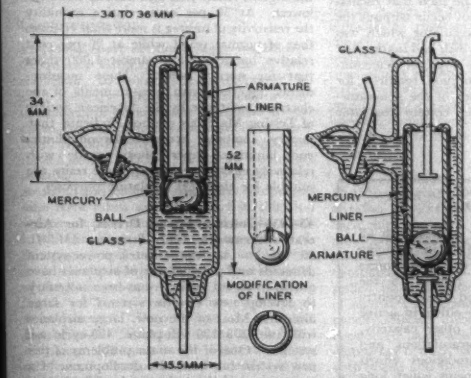

Diagram of the internal mechanism of the Sordoviso mercury switch

One of the numerous applications of this device is the provision of light signals in place of bells. In houses the ordinary electric bell or buzzer may not be heard in all the rooms, and in small houses the sound may cause confusion by being audible to neighbors. The Sordoviso switch affords a simple means of associating the bell circuits with the light circuits so that when the bell push is pressed, the lights, if in operation, are dimmed and, if not in use, are switched on. Thus a silent, light signal takes the place of the sound. To effect this purpose the switch is incorporated with a relay, the solenoid of which is connected in series or in parallel with the bell; while the mercury switch is connected in series with one of the leads from the lighting mains through a four-way rotary switch, which enables adjustment for day, night, and for other conditions to be made. The switching on or the dimming of the lights does not last for more than a second or two, owing to the time-control feature just described, but the signal is positive and unmistakable. The equipment is easily installed; does not interfere with existing wiring, and can be adapted to meet many requirements. In the Sordoviso staff-locating system a number of colored or numbered lights are used; by combinations of these as many as 50 different calls are possible. From a transmitting post to the receiving posts where the lights are installed only two wires of the type used for bells are required.

Relays and contactors fitted with these switches provide a flexible and efficient means of controlling electrical circuits. Standard units are capable of controlling double, triple, and multiple pole circuits up to 24 separate circuits. Here the small energizing current required is an important feature and the adoption of delayed action enables the respective circuits to be opened and closed after a predetermined interval or in a given sequence; the period of delay may be varied from one quarter of a second to five minutes. Similar equipment is adapted to the control of street lighting systems, where the time-delay action is useful in securing a gradual process of switching on, section by section. Flashing signs can be controlled likewise, the rate ranging from 90 to 180 flashes per minute. In many of these applications the immunity of the switch against humidity, acid fumes, and the action of the atmosphere in general is an important feature.

INSTITUTE ACTIVITIES

Fall Technical-Paper Program Announced—Discussion Closes October 15

Due to travel restrictions and the cancellation of meetings, the third series of technical papers to replace that which normally would have been presented at the Pacific Coast technical meeting, is offered for discussion by mail.

The program features a variety of subjects and two important symposiums, one on high-frequency cables, the other on central-station auxiliaries.

The symposium on high-frequency cables consists of 17 contributions and four summaries of discussions by authors who have taken a prominent part in the theory, development, and manufacture of high-frequency cables. This development has grown almost into an industry within itself and represents one of the important contributions to World War II in the field of communication. The symposium is presented in a report of the conference on high-frequency cables sponsored by the AIEE committee on communication with the co-operation of the Army-Navy Radio-Frequency Cable Co-ordinating Committee, Lieutenant Commander John H. Neher, chairman.

The symposium on central-station auxiliaries is arranged to present an up-to-date cross section of the existing practices as well as present trends in the design of systems and equipment. The points of view of operating companies and large electrical manufacturers will be brought out in several papers and such aspects of the subject as reliability, space factor, "unit-type" station design, types of electric drives, and degrees of protection will be considered. The symposium like the one on high-frequency cables is the outgrowth of a conference held during the winter meeting and it is sponsored by the AIEE committee on power generation.

In addition, other papers will be offered in the fields of air transportation, applications of statistical methods, communication, basic sciences, power generation, power transmission and distribution, protective devices, industrial power applications, capacitors for induction and high-frequency heating, and electric machinery.

Pamphlet copies of papers, for which abstracts appear in the section immediately following, may be ordered, at prices shown, from the AIEE Order Department, 33 West 39th Street, New York 18, N. Y. Coupon books in five-dollar denominations are available. An order form is included with the announcement of the program that is being mailed to members in the United States and Canada.

If you have had experience along the lines of the subject matter in any of the papers, help advance the profession by submitting your remarks in writing. Discussion should be mailed in triplicate before the closing date of October 15, 1945, to C. S. Rich, secretary of the technical-program committee, AIEE, 33 West 39th Street, New York 18, N. Y. The papers and approved discussion ultimately will be published in AIEE *Transactions;* most of the papers also will appear in *Electrical Engineering*.

ABSTRACTS • • • •

Air Transportation

45-154—Instability in D-C Aircraft Systems; *H. B. Bunce* (*A* '43), *J. C. Cunningham* (*A* '42), *W. M. Davidson* (*A* '42). *20 cents.* A laboratory and theoretical study was made to determine the causes and methods of combating an unstable oscillatory-voltage condition which has been encountered in aircraft d-c electric systems using types *P*-1, *P*-2, and *R*-1 generators with carbon-pile voltage regulators. The generator characteristics were found to be such that oscillatory instability would not occur without the presence of a voltage regulator which was out of adjustment and which had inadequate damping. A method is given for determining the amount of damping required for stable operation in terms of the generator-field time constant and certain regulator characteristics.

—VICTORY—

Electrical Engineering unites with all the members of AIEE in rejoicing over the conquest of evil by the forces of democracy and right. To the members who served their country abroad or at home—either in active combat or in some other capacity, it extends its congratulations and thanks for their prodigious efforts resulting in achievements which long after the "days of our years" will redound to the benefit of peoples everywhere.

• • •

In this new era of peace and progress *Electrical Engineering* carries on as it has in the past—reporting and reviewing all advances in electrical engineering—but with a more definitive responsibility in anticipating or in announcing the improved implements of science.

—PEACE—

45-158—Parallel Operation of Main-Engine-Driven 400-Cycle Aircraft Generators; *L. G. Levoy, Jr.* (*M* '43). *20 cents.* This paper reports progress in the development and testing of variable-ratio drives and governors for parallel operation of aircraft alternators driven from the main engines. Preliminary tests have been made demonstrating successful parallel operation of such drives under various conditions of acceleration and loading. The general system of operation and results of some of the first tests are described in this paper. The conclusion is reached that the operation of 400-cycle a-c alternators for the supply of auxiliary power in large aircraft, driven from the main engines through variable-ratio drives, is feasible and parallel operation of these alternators is practical.

45-161—The Electrical Resistivity of Resin-Treated Wood and Laminated Hydrolyzed-Wood and Paper Base Plastics; *R. C. Weatherwax and A. J. Stamm. 20 cents.* The volume electrical resistivity of 10 species of wood, impreg and compreg made therefrom, and laminated paper and hydrolyzed-wood plastics were determined in the partially oven-dry condition and in equilibrium with four different relative humidities ranging from 30 to 90 per cent. Impreg gave the highest resistivities and normal wood the lowest. At 30 per cent relative humidity the resistivity of impreg is more than 10 times that of normal wood while at 90 per cent relative humidity it is almost 1,000 times that for normal wood. These measurements, together with measurements of the electrical resistance by the American Society of Testing Materials method, indicate that impreg, compreg, hydrolyzed-wood plastic, and laminated-paper plastic made with relatively electrolyte-free phenolic resins are suitable for electrical insulating purposes.

45-163—Constant-Speed Drives for Aircraft Alternators; *C. J. Breitwieser* (*M* '44). *20 cents.* As the electric-power-system demands and physical size of airplanes have grown in recent years, it has been necessary to develop new electric systems for large aircraft. Most of the new, large airplanes will use 208/120-volt-phase 400-cycle a-c systems. One of the main problems of this new system has been the development of a constant-speed drive to couple the alternators to the main engines of the airplane. This paper discusses this problem, and describes several types of constant-speed drives. The salient features of finite-ratio gear systems, infinite-ratio mechanical couplings, and hydraulic couplings are outlined, and their kinematics briefly described.

45-165—Resonant-Circuit Constant-Current Regulators; *G. M. Kavern* (*A* '40). *15 cents.* Airport approach and runway marker light circuits are quite similar to the usual street-lighting circuits, except that the important additional feature of brightness control is required. Standard moving-coil

regulators were found to be unsatisfactory for this purpose, so the development of resonant-circuit constant-current regulators with built-in brightness control was fostered by the Army Air Forces. Four years of service have proved regulators of this type to be entirely satisfactory, and they have been adopted as standard by the Army, Navy, and Civil Aeronautics Administration. Resonant-circuit regulators have no moving parts, and operate at high efficiencies and power factors, even at light loads. Detailed performance data, together with a comparison of resonant-circuit and moving-coil regulators, are presented.

Basic Sciences

45-139—The Self-Inductance of a Toroidal Coil Without Iron; *H. B. Dwight* (*F'26*). *15 cents.* If a nonmagnetic bar is bent to form a ring and a single layer of wire is wound around it, the self-inductance of the toroidal coil so formed is given by well-known short expressions. In this paper is given a computation for the inductance of a toroidal coil of rectangular section and thick winding. The magnetic flux passes through the rectangle around which the wire is wound and through four parts of the cross section of the winding, each part having the shape of a trapezoid. A separate algebraic formula is derived for the flux linkages of each part, except that the two parts at the ends of the coil are alike. The computation is believed to have good accuracy for usual cases, but it is not so precise as most inductance computations for cylindrical coils. A numerical example of a 3,000-turn coil is given.

Communication

45-145—Report of Conference on Radio-Frequency Cables; *AIEE committee on communication. 65 cents.* The development of solid dielectric radio-frequency cables was the subject of a conference sponsored by the committee on communication and the Army–Navy Radio-Frequency Co-ordinating Committee at the AIEE 1945 winter technical meeting. Prominent engineers of the Government and of many industrial companies who have taken an active part in this development presented papers and participated in the discussion. This is a compilation of the papers and the discussion and covers from a broad viewpoint: "The Development of Radio-Frequency Cables in the United States," "The General Characteristics of Polyethylene," "Polyethylene as a Cable Insulation," "Dielectric Strength of Polyethylene," "Properties of Different Polyethylenes," "Radio-Frequency-Cable Manufacturing Methods," "General Consideration of Radio-Frequency-Cable Design," "Losses in Radio-Frequency-Cable Components," "Radio-Frequency-Cable Power Ratings and Stability," "Types of Cables and Specifications," "Shielding Characteristics of Radio-Frequency Cables," "Design Considerations of High-Frequency Twin-Conductor Cables," "Methods of Electrical and Mechanical Testing of Radio-Frequency Cables at the Naval Research Laboratory," "Electrical Tests Over a Range of Frequencies," "The S-Function Method of Measuring Attenuation of Coaxial Radio-Frequency Cable," "Corona Initiation Measurements of Polyethylene and Rubber Cables," and "A Corona Voltmeter."

45-146—A Study of Wave Shapes for Radio-Noise-Meter Calibrations; *C. W. Frick* (*A'19*). *30 cents.* It is shown through experiment and calculation that the radio-noise meters now available are used to better advantage as to accuracy and intercomparison of results when calibrated on a square wave instead of the commonly used sine-wave signal generators. Wave generators of different designs are analyzed and compared as to suitability for calibration purposes. Tests are described wherein both the present and the proposed calibration methods are employed. Noise meters built to present accepted specifications checked reasonably well with either calibration method. However, when a noise meter and a receiver setup were calibrated on sine waves, differences as much as three to one were found. The square-wave calibration materially reduces such differences, in these tests to an average of 15-per-cent difference between instruments including the receiver. It is concluded that suitable generators can be built which are stable and can be used as standards for noise-meter calibrations.

45-149—Optimum Air Gap for Various Magnetic Materials in Cores of Coils Subject to Superposed Direct Current; *V. E. Legg* (*M'37*). *20 cents.* The design of coils used as chokes in a-c circuits which must also carry direct current is complicated by the reaction of the air gap on the distribution of a-c and d-c magnetomotive forces between core and airgap. Consideration has been given to the general problem of adjusting the size of magnetic core, air-gap length, and number of turns in the winding of a coil to fulfill specifications as to inductance, resistance, and d-c carrying capacity. The mathematical means have been worked out for fulfilling specified conditions with a minimum quantity of core materials whose permeability and reversible-permeability curves are given. Calculations have been made for several typical materials to illustrate the method of utilizing this type of analysis.

45-155—Judging Mica Quality Electrically; *K. G. Coulter. 25 cents.* A threatened mica shortage, resulting from an unprecedented wartime demand for mica capacitors used in electronic communication equipment by the Armed Forces, was forestalled by rigid conservation measures, use of alternate materials, and the use of electrically selected mica from types previously considered unsuitable for capacitor use. By employing two electrical tests in combination with visual and physical requirements, mica was selected from plentiful stocks of visually lower quality types of mica, which effectively increased the supply of capacitor mica by 60 per cent. This method of electrically judging the quality of raw mica was given a thorough commercial trial and found both practicable and reliable.

Electric Machinery

45-143—Per-Unit Impedances of Synchronous Machines—II; *A. W. Rankin* (*A'38*). *15 cents.* Part I of this paper presented generalized formulas for the per-unit impedances of synchronous machines and showed that those internal machine impedances which cannot be measured from the stator terminals are subject to misinterpretation and misuse unless the rotor-current bases on which they have been calculated are explicitly defined. Part II brings together and evaluates the four major rotor-current bases which are in use in contemporary literature and illustrates quantitatively the magnitude of the possible errors involved in the misapplication of per-unit impedances calculated on a rotor-current base not explicitly defined. One specific base current is defined and evaluated, and its adoption as a preferred base is suggested. Standardization on one base-current ratio for all per-unit impedance calculations would make the published formulas more widely applicable and would tend to eliminate errors due to any inadvertent change of rotor-current base in the calculation of the various impedances.

45-156—Dielectric Strength and Protection of Modern Dry-Type Air-Cooled Transformers; *P. L. Bellaschi* (*F'40*), *Edward Beck* (*M'35*). *15 cents.* The wide acceptance of the dry-type transformer in industry naturally has increased interest in its application and standardization. In this paper impulse levels and methods of protection for this type of apparatus are presented and discussed. Applications are classified conveniently as unexposed, quasi-exposed, exposed, and highly exposed. Until recently the principal application has been to circuits unexposed to lightning, for which in general no surge protection is required. This recommendation likewise holds for quasi-exposed circuits, that is, where there are intervening oil-immersed transformers between the dry-type transformer and a highly exposed circuit, provided the former are properly protected on the exposed side. On highly exposed circuits protective devices are recommended on the incoming lines, preferably 500 to 1,000 feet from the transformer, in addition to low-ratio arresters at the transformer terminals. The low-ratio arresters are the types developed for the protection of rotating machines. Where the exposure is not severe, protective devices on the line may be omitted. Actual tests are presented which bear out the basis and reasons for these recommendations.

45-162—Fundamentals of the Amplidyne Generator; *J. L. Bower* (*M'45*). *30 cents.* The author presents an analysis of the transient and steady-state response of the Amplidyne generator in operational form. Standard tests for the determination of Amplidyne characteristics are described, and are explained theoretically by reference to the analysis. The effects of hysteresis and eddy currents, and the very important commutation problem, receive attention in the discussion.

45-166—Wound and Dummy Rotor Method of Quality Control and Trouble Shooting of Induction Motor Windings and Cores; *P. H. Trickey* (*M'36*). *15 cents.* Two of the six constants which determine induction motor performance characteristics, X_0, open circuit reactance and F_e, iron loss may be investigated and controlled by two somewhat similar methods of testing. "Dummy" rotors made like a normal squirrel-cage rotor, but without the squirrel cage

may be used in very sensitive tests to determine small variations and defects in stators. "Wound" rotors, where the rotor winding produces the excitation for the flux, provide very sensitive tests for the permeance and iron loss of stator cores. They also make very useful turn counters. For investigation and research, normal frequency gives readings in the same order as in normal operation. For particularly sensitive testing, high frequency such as 500 or 1,000 cycles is often used. Armatures from repulsion motors and d-c motors will often make emergency test rotors for such tests.

Induction and Dielectric Heating

45-137—Capacitors for High-Frequency Induction-Heating Circuits; *F. M. Clark (A '24), M. E. Scoville (M '41). 20 cents.* Increased military production has accelerated the application of high-frequency heating where accurate control of temperature for short intervals is fundamentally important. The heating of metals by induction has been widely applied. The present paper describes the development of a new type of dielectric liquid called Lectronol. Capacitors containing this liquid are particularly well adapted for use in the tank circuit of electronic heaters used in induction heating. The capacitor is water cooled and is housed in a hermetically sealed completely filled nonmagnetic container so constructed as to provide sufficient flexibility to take care of the liquid expansion due to thermal changes. The capacitor is noteworthy because of the absence of cellulose sheet insulation, satisfactory operation being entirely dependent on the superior insulating properties of the Lectronol. Capacitors containing this liquid are characterized by low dielectric loss and high dielectric strength over the frequency range utilized in power oscillators. The capacity per unit volume is approximately twice that obtained with mineral oil. The electrical characteristics of the capacitor are stable under severe conditions of use.

Industrial Power Applications

45-140—Electric Power in a Steel Plant; *R. W. Graham (M '31). 15 cents.* This paper gives a brief summary of the various uses of electricity in a steel plant with a description of the power system necessary to supply the various equipment. This is followed by a description of the relay installation on the transmission system for sectionalizing system faults and machine protection.

45-164—Maintenance of Good Brush Performance; *W. C. Kalb (F '40). 20 cents.* There are certain criteria by which the performance of brushes in respect to their three major functions should be judged. Successful performance of these functions necessitates care in the preparation and maintenance of the commutator or slip ring surface, and in the installation of the brushes on the machine. The nature of the commutator surface film has a marked influence on brush performance, and there are numerous factors affecting its development and maintenance. The trend of design toward higher commutator speed gives increasing importance to those factors which affect the intimacy of contact between brushes and commutator. Systematic analysis of observed indications of unsatisfactory operation simplifies identification of the primary fault and restoration of good brush performance.

Power Generation

45-139—Control of Load, Frequency, and Time of Interconnected Systems; *C. K. Duff (M '41). 25 cents.* The general problem is stated and typical solutions indicated. Characteristics of governors and of frequency- and load-control devices are explained briefly, and effects on generator and tie-line loads are summarized. To illustrate the principles enunciated, interconnected systems in southern Ontario and adjacent portions of Quebec, totaling 1,650,000-kw generating capacity are described, as well as operating experience with automatic frequency control and automatic load control of two ties, one of which is a 45,000-kw frequency-changer set interconnecting systems of relatively large capacity.

45-150—Power Systems for Auxiliary Drives in Steam-Electric Stations; *J. B. McClure (A '29), S. I. Whittlesey (A '45). 25 cents.* The general use of a-c motor-driven auxiliaries in steam-electric stations, together with the increased acceptance of factory-assembled equipment for power distribution, now makes it opportune to discuss the design of the power system for these auxiliaries. As a result of discussions with several operating groups, and after studying various types of auxiliary power systems, the following general conclusions, which should serve as a guide in planning power systems for auxiliaries, have been reached: a separate auxiliary power system should be considered for each boiler; power supply from the main generator leads is being increasingly used; the preferred voltages are 460 and 2,400 volts; it is economical to use a single-voltage 460-volt system where the required transformer capacity per boiler does not exceed 1,000 kva; a dual-voltage system comprising 2,400 and 460 volts should be considered where the required transformer capacity per boiler is 1,500 kva or greater; and in a dual-voltage system motors up to at least 250 horsepower can be applied economically to 460 volts. In addition the paper gives estimating data for auxiliary power requirements which will permit preliminary system designs. There also are included several suggested system arrangements; ratings and features of available equipment for this type of service; and tables which will simplify the proper applications of these equipments.

45-151—Electric Drives for Steam-Electric Generating-Station Auxiliaries; *W. R. Brownlee (M '38), J. A. Elzi (M '38). 15 cents.* The exclusive use of electric drives for all auxiliaries in modern steam-electric generating stations has a background of several years of successful operation on a number of power-supply systems and has shown gratifying over-all reliability and economy. As brought out by this paper, these results have been achieved through co-ordinated design backed by extensive tests. The basic requirements of the auxiliary drives are analyzed, together with the motor applications to co-ordinate with them. Thorough consideration has been given to the vital question of power supply for the auxiliaries, and definite conclusions are given as to the scheme which provides the desired objectives. No small part of the successful performance of the all-electric drive depends on the correct application of motor control and protection. The test results which have been included demonstrate the satisfactory performance that can be secured from the co-ordinated all-electric design during the most severe operating conditions and provide useful information for future designs.

45-152—Auxiliary Power Supply for Generating Stations; *V. E. McCallum (M '38). 15 cents.* All recent electric generating stations have been built with a major portion of their auxiliaries driven by motors, and the present station is dependent at all times on the integrity of the auxiliary power system; therefore, this system must be designed for maximum reliability. Where the electric station is a part of an interconnected system and the station busses are segregated and relayed for fault protection, it is suggested that the station generator busses are the most reliable source of power and that a separate and independent auxiliary power service unit be provided to serve the maximum amount of generating capacity, the loss of which could be sustained by the system without undue disturbance.

45-153—Central-Station Auxiliary-Drive Motors for Constant and Adjustable Speed; *Hal Gibson (A '44). 15 cents.* Central-station auxiliary drives must be selected with the object of obtaining maximum reliability. This paper reviews the general recommendations for these motors from the standpoint of type, enclosures, insulation, bearings, adjustable speed motors, and high-speed gears and motors. The stability of a wound-rotor induction motor with secondary control below 50 per cent of rated speed also is discussed briefly, as is power savings for fan drives with wound-rotor and two-speed motors over constant-speed motors and throttling dampers.

Power Transmission and Distribution

45-141—The Frequency of Occurrence and the Distribution of Lightning Flashes to Transmission Lines; *R. H. Golde (A '42). 30 cents.* From physical principles a method has been developed of calculating the protection afforded by a lightning conductor or similar structure. The protective range is found to vary with the amplitude of the lightning current. The numerical results derived are applied to a calculation of the distribution of direct strokes between towers and phase wires of a transmission line, the increase in the number of strokes due to the installation of earth wires, and the distribution of strokes to towers and earth wires in the latter case. The frequency of flashes to earth over a given area is shown to be related to the isokeraunic level of the district involved. Numerical results obtained for the aforementioned problems are compared with field observations.

45-144—Sag and Tension Calculations for Cable and Wire Spans Using Catenary Formulas; *J. F. Nash (M '26), J. F. Nash, Jr. 25 cents.* This paper develops a new method for solving sag and tension problems for wire and cable spans. This mathematically exact procedure, though derived entirely from catenary formulas and derivations thereof, uses working formulas requiring only simple arithmetical calculations which can be handled by engineering-office clerical personnel. Laborious calculations and trial-and-error computations necessary with other methods are eliminated. This method develops not only sags, tensions, and cable lengths for the various final and initial conditions of the design span but also similar data for other length spans related to the design span. The method also outlines a new exact method for sag and tension calculations for hillside spans and previously unpublished relationships between sags, tension, and cable lengths.

45-160—Costs Study of 69- to 230-Kv Underground Power-Transmission Systems and Tie Lines; *J. G. Holm (M '29). 30 cents.* Thirty underground power-transmission systems and tie lines have been designed and their capital and annual costs determined. The 69-kv lines have solid and oil-filled cables, and the 138-kv and 230-kv lines have oil-filled cables. Systems have ratings from 50,000 to 600,000 kva. Power is transmitted at distances of ten and 15 miles over one to four circuits. System costs are those immediately preceding the current war; they are based on data obtained from manufacturers, as well as on actual construction data. The results give an economic zone of application of various cables. They show that there is an economic relationship between the transmission voltage and the block of power transmitted. Curves are given from which costs of various underground systems or their parts may be estimated at prices similar to or different from those taken in the study. The optimum system rating and voltage most suitable for certain conditions may be determined from the data given.

Protective Devices

45-147—Lightning Arresters for Distribution Apparatus; *Edward Beck (M '35), A. D. Forbes (M '42). 20 cents.* The major item on distribution systems that requires lightning protection is the distribution transformer. Protection is an integral part of the completely self-protected transformer. When lightning arresters are installed separately, two general types are used, the expulsion and the valve types. Their differences in operating characteristics and mechanical construction are discussed. The protective characteristics of the arresters are compared with the impulse withstand tests for distribution transformers.

45-148—Phase-Comparison Carrier-Current Relaying; *A. J. McConnell (A '36), T. A. Cramer (A '41), H. T. Seeley (A '27). 30 cents.* This paper describes a carrier-current differential-relaying system which operates to trip both terminals of a faulted line section simultaneously when fault currents are greater than predetermined limits. All application limits are given in a section outlining application procedure. The system employs a single carrier-current channel. Therefore, a single quantity for transmission and comparison must be derived from phase-fault and ground-fault currents. Reasons for the choice of the components of the single quantity are developed by analysis of the requirements of the various types of faults. The result is an overcurrent relaying system which

1. Does not require current in excess of maximum full-load current, except during three-phase faults.

2. Does not depend upon the operation of any relay for the transmission of the carrier-current blocking signal, except during three-phase faults.

The various relay components are described, and the characteristics of these components and of the over-all system are given.

Lamme Medal Nominations

Attention is called again to the opportunity open to any Institute member to submit nominations for the 1945 AIEE Lamme Medal. All nominations must be received not later than December 1. For particulars see *Electrical Engineering*, June 1945, page 227.

The 1944 medal was awarded to S. H. Mortensen, chief electrical engineer, Allis-Chalmers Manufacturing Company, Milwaukee, Wis. An account of the presentation of the medal to him was published in the August *Electrical Engineering*, page 300.

AIEE Member in the News

Among those who worked to perfect the powerful atomic bomb, the news of the first application of which stunned the world on August 7, 1945, is Doctor Vannevar Bush (A '15, F '24) director of the Office of Scientific Research and Development. His recent report to the President, "Science the Endless Frontier," which recommends a program for postwar scientific research is referred to elsewhere in this issue. Doctor Bush was one of the scientists who "stood by" in the trial of the first man-made atomic explosion set off July 16 at the Alamogordo Air Base in the New Mexico desert and saw the steel tower, atop of which the bomb was hauled on July 14, vaporized, leaving only a huge sloping crater.

A few technical details of the atom bomb released by the Army will be published in a forthcoming issue.

AIEE Board of Directors Meeting

The regular meeting of the board of directors of the American Institute of Electrical Engineers was held at Institute headquarters, New York, N. Y., June 27, 1945.

Petitions were presented for the election of Doctor Gano Dunn and Doctor Frank B. Jewett as Honorary Members, and members of the board present voted unanimously for their election. Affirmative votes were received from all absentees.

The finance committee reported, and the board approved, expenditures in June amounting to $33,454.03, which included payment for the 1945 *Year Book*.

An appropriation of $152 was made as the Institute's share of an expense to be incurred by the joint committee to study the organization of the engineering profession, in the preparation by Engineers' Council for Professional Development of a classified list of engineering societies.

The formation of a Beaumont Section was authorized, upon recommendation of the Sections committee, with territory in the following Texas counties: Jefferson, Orange, Hardin, Polk, Sabine, Tyler, Jasper, Shelby, Newton, Trinity, San Augustine, Angelina, and Nacogdoches.

Recommendations of the Standards committee for the appointment of the following AIEE representatives were approved:

L. C. Larson to Sectional Committee C70 (Domestic Electric Flatirons) and Sectional Committee C71 (Household Electric Ranges), to replace R. E. Johnson, resigned.

F. P. Kuhl to Sectional Committee Z14 (Drawings and Drafting Room Practice), to replace H. W. Samson, resigned.

G. S. Lunge to Sectional Committee Z32 (Graphical Symbols), to replace H. W. Samson, resigned.

S. B. Ingram to Sectional Committee C60 (Vacuum Tubes for Industrial Purposes), to replace M. J. Kelly, resigned.

A. C. Monteith to Sectional Committee C67 (Voltages Below 100), to replace C. A. Powel, resigned.

Upon recommendation of the Standards committee, the board approved a revision, prepared by the committee on marine applications, of AIEE Standard 45 "Recommended Practice for Electrical Installations on Shipboard," and approved for publication as a report of a proposed standard, proposed Standard for "Expulsion-Type Distribution Lightning Arresters," prepared by the committee on protective devices.

Final reports were received from various special committees and representatives.

Other matters were discussed, reference to which may be found in this or future issues of *Electrical Engineering*.

Other actions taken included the following:

Minutes of the meeting of the board of directors held May 29, 1945, were approved.

Recommendations adopted by the board of examiners at a meeting on June 14, 1945, were presented and approved. Upon recommendation of the board of examiners, the following actions were taken: seven applicants were transferred to the grade of Fellow; 45 applicants were transferred, and 39 were elected to the grade of Member; 221 applicants were elected to the grade of Associate, and 148 Students were enrolled.

Those present were:

President—Charles A. Powel, East Pittsburgh, Pa. *Past presidents*—N. E. Funk, Philadelphia, Pa., H. S. Osborne, New York, N. Y. *Vice-presidents*—L. A. Bingham, Boulder, Colo., C. B. Carpenter, Portland, Oreg., M. S. Coover, Ames, Iowa, J. F. Fairman, New York, N. Y., W. J. Gilson, Toronto, Ont., R. T. Henry, Buffalo, N. Y., C. W. Ricker, New Orleans, La., R. W. Warner, Austin, Tex., W. E. Wickenden, Cleveland, Ohio. *Directors*—P. L. Alger, Schenectady, N. Y., K. L. Hansen, Milwaukee, Wis., C. M. Laffoon, East Pittsburgh, Pa., T. G. LeClair, Chicago, Ill., F. R. Maxwell, Jr., Pensacola, Fla., M. J. McHenry, Toronto, Ont., C. W. Mier, Dallas, Tex., S. H. Mortensen, Milwaukee, Wis., W. B. Morton, Philadelphia, Pa., D. A. Quarles, New York, N. Y. *Treasurer*—W. I. Slichter, New York, N. Y. *Secretary*—H. H. Henline, New York, N. Y.

Those present by invitation were:

Incoming officers—S. S. Wyatt, Cincinnati, Ohio; F. L. Lawton, Montreal, Que.; J. K. Norris, Jackson, Mich., L. M. Robertson, Denver, Colo., H. B. Wolf, Charlotte, N. C.

PERSONAL ••••

Frank Baldwin Jewett (A '03, M '10, F '12) retired vice-president, American Telephone and Telegraph Company, New York, N. Y., and president of AIEE, 1922–23, was elected an Honorary Member of the Institute, June 27, 1945. Doctor Jewett was born at Pasadena, Calif., September 5, 1879. In 1898 he was graduated from Throop Polytechnic Institute (now the California Institute of Technology) with the degree of bachelor of arts. Following his graduation he engaged in graduate study in physics, mathematics and chemistry at the University of Chicago, and during his last year there he acted as research assistant of the department of physics, receiving the degree of doctor of philosophy in 1902. Doctor Jewett then went to the Massachusetts Institute of Technology, Cambridge, where he continued study and was instructor in physics and electrical engineering. In 1904 he entered the employ of the American Telephone and Telegraph Company and was shortly thereafter given charge of its engineering research work. From 1908–1912 he was transmission and protection engineer, responsible for the development of equipment. In the last-mentioned year he became assistant chief engineer of the Western Electric Company, New York, N. Y., and in 1916 was appointed chief engineer in charge of the research laboratories. Six years later he was promoted to vice-president. This position extended his duties to include the supervision of all the manufacturing operations of that company in America, together with the direction of the sales and distribution of its manufactured product. In addition he co-operated in the development of the vacuum tube, the telephone repeater, and the high-speed submarine telegraph cable, and the building of the transcontinental telephone lines. In 1917 he was commissioned a major in the Signal Corps, United States Army Reserves, and was later promoted to lieutenant-colonel in the Signal Corps of the regular army. For his service during the war, he received the distinguished service medal. In 1925 he became vice-president of the American Telephone and Telegraph Company, in direct charge of the department of development and research, and at the same time was elected president and a member of the board of directors of the Bell Telephone Laboratories, Inc., conducting the laboratory and research work, and in 1940 he became chairman of the board of directors. Doctor Jewett retired from the American Telephone and Telegraph Company in 1944. In that year he was awarded the doctor-of-science degree by Boston University, and the doctor-of-laws degree by Norwich University. In his honor in September 1944 the Frank B. Jewett Fellowships were inaugurated by the American Telephone and Telegraph Company. These fellowships provide for the full-time continuation of academic research. His contributions to AIEE affairs are outstanding. In addition to being president, he was manager 1915–1918 and vice-president 1918–1919 and has represented the Institute on the Engineering Foundation Board, the National Research Council, the John Fritz Medal Board of Award, the Hoover Medal Board of Award, the American Engineering Council, and the Iwadare Foundation. Among the many AIEE committees on which he has served are those on: the Edison Medal, executive, law, protective devices, research, Standards, telegraphy and telephony, education, co-ordination of Institute activities, and the code of principles of professional conduct. His scientific attainments have been recognized by the additional honorary degrees of doctor of science, New York University and Dartmouth in 1925, from Columbia University and the University of Wisconsin in 1927, and from Rutgers University in 1928; by the honorary degree of doctor of engineering from the Case School of Applied Science in 1928; and the Fourth Order of the Rising Sun, which was bestowed upon him by the Japanese Government. Doctor Jewett has been the recipient of the Edison Medal, Faraday Medal, Franklin Medal, and John Fritz Medal. He was elected president of the National Academy of Sciences in 1939, and re-elected in 1943. He has been active in The Engineering Foundation, and in the National Research Council.

F. B. Jewett

C. F. Kettering (A '04, F '14) vice-president in charge of research, General Motors Corporation, Dayton, Ohio, will direct a new Cancer Research Institute, in New York, N. Y., a $4,000,000 fund for which Alfred P. Sloan, Jr., chairman of the corporation, has recently granted. Doctor Kettering, who will concentrate on the organization of industrial techniques for cancer research, was born at Loudonville, Ohio, and was graduated from the course in electrical engineering at Ohio State University in 1904. He has been the recipient of the honorary degree of doctor of engineering and doctor of science from several universities, and many other honors have been conferred on him. Early in his career he was associated with the Star Telephone Company, Ashland, Ohio and later with the National Cash Register Company he developed the electrically driven cash register. In 1916 he established a research laboratory at Dayton which was taken over by the General Motors Corporation in 1920, and it was moved to Detroit in 1925. Doctor Kettering was elected to receive the Washington Award of the AIEE in 1936 and was awarded the John Fritz Medal for 1944 "for notable accomplishments in the field of industrial research which have contributed greatly to the welfare of mankind and of the nation."

Gano Dunn (A '91, M '94, F '12) president of the J. G. White Engineering Corporation, New York, N. Y., for more than 30 years was elected an Honorary Member of the Institute, June 27, 1945. Mr. Dunn was born in New York, N. Y., and received the bachelor-of-science degree from the College of the City of New York in 1889, the degree of electrical engineer from Columbia University in 1891, and master-of-science degree from the former college in 1897. During the period of 1886 to 1891 he worked for the Western Union Telegraph Company as a night telegraph operator, and in 1891 accepted a position with the Crocker-Wheeler Company. His promotion with that company was rapid and he became its vice-president and chief engineer in 1911. In that same year he was offered a vice-presidency of J. G. White and Company. He assisted Mr. White in organizing the J. G. White Engineering Corporation and three years later became its first president. During World War I the J. G. White Engineering Corporation built many important government projects, such as the great steam plant at Muscle Shoals, nitrate plants, and government aviation terminals. Mr. Dunn has taken an active part in the management of the AIEE. He has served on its governing board as a manager and vice-president, and during 1911–12 he was its president. He has also served on many committees of AIEE and other societies which include among them the following: code of principles of professional conduct; iron and steel industry; public policy; John Fritz board of award; licensing of engineers; education; American Association for the Advancement of Science, and the board of trustees, United Engineering Societies. From 1923 to 1928 Mr. Dunn was chairman and chief executive officer of the National Research Council. In 1937 and in 1939, respectively, he was awarded the Edison and the Hoover Medal, AIEE. In 1940 he was senior consultant on power, Office of Production Management, and served as its special consultant on capacity of the steel industry in 1941; in 1943, honorary president, Pan American Society; 1944, president, Phi Beta Kappa associates, member of Governor Dewey's committee on technical industrial development, and honorary member American Society of Mechanical Engineers; in 1945 chairman, executive committee of the Pilgrims; chairman, American Executive Committee of the World Power Conference; overseas representative for the United States, Institution of Electrical Engineers of Great Britain.

Gano Dunn

John Mills (A '11, F '23) director of publication since 1925 of the Bell Telephone Laboratories, Inc., New York, N. Y., retired as of April 30, 1945. Mr. Mills received the bachelor-of-arts degree from the University of Chicago in 1901, and the master-of-arts degree from the University of Nebraska in 1904. He also spent eight years at Western Reserve University, Massachusetts Institute of Technology, and Colorado College. In 1911 Mr. Mills became identified with the research group in long-distance transmission instituted by the American Telephone and Telegraph Company. His work formed a solid basis for the engineering of lines for repeater operation. After the transcontinental telephone Mr. Mills was assigned to the construction of stations and antennas for the transatlantic line. Immediately thereafter he was transferred to the engineering department of Western Electric Company working first on radio transmission and specifically on methods at a receiving station for reducing static. In World War I he trained in radio the group of Western Electric men who became the nucleus of the Signal Corps research and inspection group of the American Expeditionary Forces. Then in 1922 Mr. Mills began to work in personnel. With the incorporation of Bell Telephone Laboratories, Mr. Mills was named director of publication. In this capacity he took over some existing functions, such as information services to the associated companies and the public, the Bell System Historical Museum, and planned a magazine of information on the work of the Laboratories, the first issue of which appeared in September 1925. Another of his contributions was in the field of exhibits, and he assumed responsibility for their design and installation. Mr. Mills has served on several committees of the AIEE, and has been especially active on the publication committee of which he has been a member since 1941.

C. E. Stephens (M '22) vice-president, Westinghouse Electric Corporation, New York, N. Y., has retired. Mr. Stephens was born in Ferris, Texas, and attended the Ferris Institute. He joined the Westinghouse corporation in 1900 as an apprentice in the East Pittsburgh shops. Leaving the student work, he worked in the testing department and in the engineering department. After an assignment on motor insulation design and development he was made manager of the arc lighting section of the engineering department, and then was promoted to the position of illuminating engineer of the general engineering department. Subsequently he was made manager of the illuminating section of the sales department, from which position in 1917 he was transferred to the New York office as manager of the supply department. Later he was made manager of the central station division of the New York office, and in 1925 he was manager of the district, the largest within the Westinghouse district sales divisions. In 1930 he was elected commercial vice-president and two years later vice-president. He has served as vice-president of the Electrical Association of New York, vice-president of the Illuminating Engineering Society, and on the administrative board and as treasurer of the American Engineering Council Assembly. Mr. Stephens at one time served as a director of the Institute and has been active on many committees including the following: finance; code of principles of professional conduct; co-ordination of Institute activities; headquarters; executive; Popular Science award; Edison medal; production and application of light, and on the special committees on biographies and talking motion pictures; model registration law, and bust of Edison for Munich Museum.

R. T. Henry (A '24, F '33) formerly assistant chief electrical engineer, engineering department, Buffalo (N. Y.) Niagara and Eastern Power Corporation, has been appointed chief electrical engineer. He was born in Stronghurst, Ill. In 1908 he became associated with the General Electric Company at Lynn, Mass., subsequently serving Niagara Falls (N. Y.) Hydraulic Power and Manufacturing Company, Hooker Electrochemical Company, Niagara Falls; Edison Illuminating Company, Detroit, Mich., and the Niagara Electric Service Corporation. From 1918 until 1929 he was assistant electrical engineer with the Niagara Falls Power Company, and in the latter year became electrical engineer in charge of design, Buffalo, Niagara and Eastern Power Corporation, and was made assistant chief electrical engineer in 1942. Mr. Henry was a member of the National Electric Light Association serving on several committees, and was chairman of the electrical equipment committee of the Edison Electric Institute, 1942–43. He has been prominent in AIEE affairs acting as chairman of the Niagara Frontier Section for the year following August 1, 1929, and has served on many committees. These include the following: protective devices, for which he was chairman, 1932–34; technical program; Standards, for which he was chairman, 1940–42; planning and co-ordination; production and application of light; Standards council, ASA, and the Charles LeGeyt Fortescue Fellowship. Mr. Henry was awarded the 1933 AIEE national prize for the best paper on engineering practice.

Edith Clarke (A '23, M '33) engineer, central station department, General Electric Company, Schenectady, N. Y., retired July 31 after completing 26 years of service with the company. Miss Clarke was born in Howard County, Md., and received her education at Vassar College, University of Wisconsin where she studied civil engineering, and the Massachusetts Institute of Technology where she received the master-of-science degree in electrical engineering in 1919. From 1912–1915 Miss Clarke was associated with the American Telephone and Telegraph Company as computer for the research engineer, and for the next three years she was in charge of calculations in the transmission and protection engineering department. In 1919 she joined the General Electric Company as a member of the turbine engineering department. Two years later she received a leave of absence to serve as professor of physics at the Constantinople (Turkey) Women's College. In 1922 returning to the General Electric Company she went to work on technical problems dealing with the generation and transmission of power, later taking charge of engineers handling such problems as power system stability, and load distribution. She is the author or co-author of many technical papers, and wrote a book entitled "Circuit Analysis of A-C Power Systems."

F. H. Brown (A '38, F '45) sales engineer, Copperweld Steel Company, New York, N. Y., New England territory, has been transferred to the home office, Glassport, Pa., where he will be staff engineer in the general sales department. Before joining the Copperweld Steel Company, Mr. Brown was purchasing agent for the city of Bangor, Me. and prior to that he was engineer with the Electric Bond and Share Company, New York. **H. M. MacDougal** (A '40) electrical engineer, sales engineering department, succeeds Mr. Brown. In 1930 Mr. MacDougal was affiliated with the New York State Electric and Gas Corporation, Ithaca district, as assistant resident engineer, and in 1938 with the Copper Wire Engineering Association, Washington, D. C., as electrical engineer. In 1942 he became chief of the public utility unit, conservation division, War Production Board, Washington, D. C., and in 1943 became associated with the Copperweld Company.

F. E. Fairman, Jr. (M '41) formerly assistant manager, switchgear division, central station department, General Electric Company, Philadelphia, Pa., has accepted the positions of manager of the Peerless Division and a vice-president of Food Machinery Corporation, New York, N. Y. Mr. Fairman is a graduate of the United States Naval Academy, joining the General Electric Company in 1923 as a switchgear engineer at their Baltimore, Md., works. That same year he received the Coffin award for advance in air circuit-breaker design. In 1941 he was promoted to assistant manager of the switchgear division.

M. G. Crosby (M '41) former radio engineer, research department, RCA laboratories, Radio Corporation of America, Riverhead, N. Y., has joined the Paul Godley Company, Upper Montclair, N. J., where he will specialize in radio communication systems. Mr. Crosby graduated from the University of Wisconsin in 1927 with the bachelor-of-science degree and in 1943 received the electrical-engineering degree. He has been a research engineer for the communications division of the RCA laboratories since 1925 and in that position specialized in frequency modulation. In 1943 and 1944 Mr. Crosby served as expert technical consultant to the Secretary of War. He is the owner of many patents and the author of technical articles on frequency and phase modulation. He is a fellow of the Institute of Radio Engineers and the Radio Club of America and has served on the AIEE membership committee of the New York Section.

P. L. Warren (A '26, M '38) lieutenant commander, United States Naval Reserve, has returned as president and treasurer of the Royal Electric Manufacturing Company, Chicago, Ill. Commander Warren became identified with the Royal Electric company in 1936. Prior to this he had been associated with the Ohio Brass Company, also of Chicago.

R. C. McMaster (A '39) formerly instructor in electrical engineering, California Institute of Technology, Pasadena, has accepted an appointment to the staff of Battelle Institute, Columbus, Ohio, and has been assigned to its division of industrial physics. Doctor McMaster received the degrees of bachelor of science in electrical engineering from the Carnegie Institute of Technology and master of science and doctor of philosophy from the California Institute of Technology. In 1936 he became associated with the General Electric Company, Schenectady, N. Y., as a student engineer and in 1937 took the position of teaching assistant in electrical engineering at the California Institute of Technology. He left to become instructor in electrical engineering at the Case School of Applied Science, Cleveland, Ohio, in 1938, and subsequently returned to the California Institute of Technology as instructor in electrical engineering and supervisor of welding and X-ray research. Doctor McMaster is now serving on the AIEE electric-welding committee.

C. A. B. Halvorson (M '22) consulting engineer, lighting section, River Works, General Electric Company, Lynn, Mass., has retired. Mr. Halvorson joined the General Electric Company as junior test man in 1898, in 1902 became a lighting engineer, and in 1906 was named the company's first manufacturing engineer. Three years later he was appointed designing engineer of the street-lighting department and in 1930 became consulting engineer. In World War I, he designed the first floodlights used to light the Statue of Liberty and an antiaircraft searchlight for the Government and in this war has been engaged in confidential work for the Army and Navy. Mr. Halvorson is a member and past vice-president of the Illuminating Engineering Society and the Society of Motion Picture Engineers. He has served on the AIEE committee on production and application of light and is the author of several technical papers.

R. D. Bennett (F '35) captain, United States Naval Reserve, director of technical development, Naval Ordnance Laboratory, United States Navy Yard, Washington, D. C., has been awarded an honorary doctor of science degree from Union College. A graduate of Union College in 1921, Captain Bennett is the inventer of a device for measurement of cosmic rays and former professor of electrical measurements at the Massachusetts Institute of Technology, Boston. **H. V. Putman** (A '23, M '32) vice-president, Westinghouse Electric Corporation, Sharon, Pa., also received an honorary degree from Union College. Mr. Putman has been associated with Westinghouse corporation since 1925, and previously received from Union College, the degrees of bachelor of science in 1920, master of science in 1921, and doctor of philosophy in 1923.

N. R. Gibson (M '32) vice-president, Buffalo (N. Y.) Niagara and Eastern Power Corporation, has been promoted to the post of senior vice-president. Doctor Gibson has been with the company and its predecessors since 1918 when he became hydraulic engineer for the old Hydraulic Power Company, Niagara Falls, N. Y. He is chief engineer of Niagara Hudson System Companies, vice-president of Niagara Hudson Power Corporation, and president of Canadian Niagara Power Company, Ltd. In 1930 he was awarded the Elliot Creson gold medal by the Franklin Institute of Pennsylvania for his invention of the Gibson method and apparatus for measuring the flow of liquids in closed conduits.

E. S. Bundy (A '14, F '33) chief electrical engineer for the Western Division companies of Buffalo, Niagara and Eastern Power has been named chief engineer and vice-president. Mr. Bundy was graduated from Cornell University in 1911 and began work shortly after that with the Niagara, Lockport and Ontario Power Company, Syracuse, N. Y., working in various capacities in the western and central divisions of the company until 1923 when he was named electrical engineer for the company in Syracuse. In 1932 he became assistant electrical engineer for Buffalo Niagara Electric Power Corporation and in 1936 was promoted to the position of chief electrical engineer. In addition to this assignment he has also been supervising the engineering for the Niagara Hudson System since 1941.

F. R. Bacon (A '10, M '20) president, Cutler-Hammer, Inc., Milwaukee, Wis., has been elected chairmau of the board. Founder of the company, Mr. Bacon has been president from 1896 except for the years from 1924 to 1931 when he acted as chairman of the board, the position he now holds. **J. C. Wilson** (M '18) vice-president, was elected vice-president and secretary; **P. B. Harwood** (M '36, F '42) manager, engineering department, has become vice-president in charge of engineering; **Philip Ryan** (A '22, M '30) works manager, has been elected vice-president in charge of manufacturing, and **E. W. Seeger** (A '16, F '36) manager, development department, is the new vice-president in charge of development, and in addition becomes assistant secretary. All the newly elected vice-presidents have been with the company for a period of 25 years or more.

T. H. Haines (A '23, F '44) assistant vice-president and superintendent of transmission and distribution department, Boston (Mass.) Edison Company, has been appointed coordinator of management personnel, a newly established industrial-relations position within the company. During the period of Mr. Haines' work in this capacity, **E. C. Rue** (A '25, M '43) assistant superintendent, transmission and distribution department, will serve as acting superintendent. **J. F. Archibald** (M '43) assistant head of distribution operating, has accepted the promotion to head the overhead section of the transmission and distribution department, and **T. A. Pinkham, Jr.** (A '44) assistant division head, transmission and distribution department, becomes head of the underground division.

J. S. Wise, Jr. (A '96, M '27) president, Pennsylvania Power and Light Company, Allentown, has retired. A graduate of the University of Pennsylvania in 1898 with the bachelor-of-science degree in engineering, Mr. Wise gained early experience with the General Electric Company, Schenectady, N. Y., Atlantic City (N. J.) Electric Light Company, and the Auburn (N. Y.) Light, Heat and Power Company. In 1906 he became general manager and director of The Harwood Electric Company, Hazleton, Pa., and in 1913 acted in a similar capacity for the Lehigh Navigation Electric Company, Allentown. In 1922 he accepted the position as general manager of the Pennsylvania Power and Light Company, and in 1929 became its president.

T. O. Kennedy (M '18, F '39) president and general manager, Ohio Public Service Company, Cleveland, has resigned. Mr. Kennedy became associated with the public utility industry in 1907 after his graduation from the University of Missouri. In 1922 he was sent to Cleveland as vice-president and general manager of the Ohio Public Service Company, subsequently being elected president. **R. E. Burger** (F '30) president, Cities Service Power and Light Company, Jersey City, N. J., of which Ohio Public Service is a subsidiary, has been elected president and general manager to succeed Mr. Kennedy. Mr. Burger began his utility career in Ohio in 1909 and from that time until 1920 served as manager in many of the cities now served by Ohio Public Service Company.

D. W. Atwater (A '34) in charge of the illuminating engineering department, Westinghouse Electric Corporation, Bloomfield, N. J., will head the newly consolidated departments, resulting from a merger of the illuminating engineering department with the commercial engineering department, as manager of commercial engineering. Since joining the Westinghouse corporation in 1920 as a lamp engineer, Mr. Atwater has been identified with many pioneer movements in modern lighting. He was active in the illumination of the Philadelphia Sesquicentennial; Century of Progress Exposition in Chicago; Holland Tunnel, New York, N. Y., and the New York World's Fair.

C. E. Brown, Jr. (A '40) formerly vice-president, The Okonite Company, Washington, D. C., has been appointed vice-president and general sales manager to coordinate the activities of the executive offices in Passaic, N. J. Mr. Brown joined the Okonite sales organization in 1919, first serving as an agent with the Central Electric Company, Chicago, Ill., and in 1925 as manager of the company's power and light department in the territory around Chicago, Ill.

G. A. Horton (A '44) formerly project engineer, in charge of the Photometric Laboratory, United States Army Air Forces, Wright Field, Dayton, Ohio, has accepted a position as laboratory supervisor, lighting division, Westinghouse Electric Corporation, Cleveland, Ohio.

Gerhard Mauric (A '43) engineer since 1943 with Electrical Engineering and Manufacturing Corporation, Los Angeles, Calif., has been appointed chief engineer. Upon graduation from Technical University, Vienna, in 1928, with the degree of electrical engineer, Mr. Mauric became a test engineer, Elin Ag Weiz, Austria. In 1929 he accepted the position of service superintendent for Western Electric Company, Austria, engaged in instruction and supervision of service men for all of Central Europe except Germany. In 1940 he became associated with Lear Avia, Inc., Los Angeles.

A. B. Cooper (M '16, F '33) president, Ferranti Electric, Ltd., Mount Dennis, Toronto, Ontario, Canada, has been elected president of the Canadian Electrical Manufacturers' Association at its first general membership meeting in Toronto; **A. S. McCordick** (M '30) vice-president, Moloney Electric Company of Canada, Ltd., Toronto, was elected a vice-president; **L. E. Messinger** (A '30, M '44) president and managing director, Canadian Line Materials, Ltd., Toronto, has accepted the position of treasurer; and **G. W. Lawrence** (A '19) president, Sangamo Company, Ltd., Leaside, Ontario, has become a member of the executive committee.

John Romano (A '42) application engineer, Delta Star Electric Company, Chicago, Ill., has been appointed assistant sales manager. Mr. Romano became associated with the company in 1927 as a draftsman, and subsequently did work in sales, mainly the estimate and design of outdoor substations. **C. F. Bolles** (M '40) sales engineer, New York (N. Y.) office, has been named assistant manager and engineer of that office. Mr. Bolles joined the company in 1936 to do engineering work in connection with the sale of high-voltage switchgear and electrical equipment to utilities and industrials in the metropolitan area.

F. W. Godsey, Jr. (A '30, M '36) staff assistant, new products division, Westinghouse Electric Corporation, East Pittsburgh, Pa., has been appointed manager of that division. Prior to going to Westinghouse corporation he was development engineer with the Safety Car Heating and Lighting Company, and chief electrical engineer and assistant production manager for the Sprague Electric Company, North Adams, Mass. Mr. Godsey joined the Westinghouse corporation in 1940 to serve in the division he now directs.

C. L. Collens, 2d (A '07, M '40) chairman, Reliance Electric and Engineering Company, Cleveland, Ohio, has been elected president of the Associated Industries of Cleveland. Mr. Collens has served on the board of directors of the American Standards Association and of the National Industrial Conference Board, and as president of the National Electrical Manufacturers' Association, and president of the Electric Power Club.

H. B. Leidy (A '34) assistant manager, Middle Atlantic district, manufacturing and repair department, Westinghouse Electric Corporation, Philadelphia, Pa., has been appointed manager of that district and department. Mr. Leidy studied engineering at Bucknell University before obtaining a commission in the United States Army in 1917. He joined the Westinghouse corporation in 1920, serving as field engineer, salesman, and branch manager at the Wilkes-Barre (Pa.) manufacturing and repair department, and in 1942 was made assistant manager.

D. C. Ober (A '16) formerly vice-president in charge of operations, Cleveland (Ohio) Electric Illuminating Company, has been elected executive vice-president of the company. He entered the employment of the company in 1912 while still a student of the Case School of Applied Science, and in 1914 took a full-time position in the electrical-engineering department. In 1917 he became assistant in charge of the department, in 1933 he was promoted to executive engineer, later was appointed manager of operations, and subsequently became vice-president.

F. F. Fowle (A '02, M '12) head of the firm, Frank F. Fowle and Company, Chicago, Ill., has been chosen to receive the Octave Chanute medal for 1944, awarded by the Western Society of Engineers. Mr. Fowle is known for his work as consulting engineer and author, and is a member of numerous engineering and scientific societies. The medal, established by Octave Chanute during his term as president of the Western Society of Engineers, is awarded for the best papers in civil, mechanical, and electrical engineering presented before the society.

J. R. Beard (F '41) senior partner, Merz and McLellan, consulting engineers, Milburn, Esher, Surrey, England, has been elected chairman of the Association of Consulting Engineers. Mr. Beard is a past president of the Institution of Electrical Engineers.

T. R. Halman (A '36, M '43) former relay engineer, The Detroit (Mich.) Edison Company, has been appointed supervising engineer, testing and relaying, electrical system. Mr. Halman has been associated with the company since 1922.

OBITUARY • • • •

Leonard J. Moore (A '15, M '31, F '42) retired executive engineer for the Pacific Gas and Electric Company, Fresno, Calif., died June 4, 1945, in Fresno. Born April 27, 1885, in Lynnville, Iowa, Mr. Moore received the degree of bachelor of science in electrical engineering in 1908, and had the professional degree of electrical engineer conferred upon him in 1935, both being received from Iowa State College. Between the years 1908 to 1911, he was employed by the Telluride Power Company (succeeded by the Utah Power and Light Company) in Utah and Idaho as power-house operator in hydro-electric plants and later as instructor in a technical school for employees. In 1911 he entered the San Joaquin Light and Power Corporation, Fresno, to work on substation maintenance and construction, and subsequently became load dispatcher in 1912, engineering assistant to the general superintendent in 1916, in charge of design and construction in 1918, executive engineer in 1921, and was named division executive engineer, San Joaquin power division, Pacific Gas and Electric Company, Fresno, in 1938. In that year that company took over the San Joaquin Light and Power Corporation. He retired from this company in 1944. Mr. Moore served as chairman for the engineering section of the Pacific Coast Electrical Association, and was a member of the electrical-apparatus committee of the National Electric Light Association. He was a former member of the AIEE committees on protective devices and domestic and commercial applications, and was the author of numerous technical articles.

Walton Charles Poole (M '39) chief electrical engineer of the Sinclair Refining Company in East Chicago, Ill., died recently. Mr. Poole was born in Chelsea, Okla., in 1889, and received his education at the Willie Halsell College in Vinita and at the University of Oklahoma. In 1907 he became associated with the United States Navy as electrician in the fire control and communications section. In 1912 and for seven years thereafter he served the Vinita (Okla.) Producing and Refining Company as electrical superintendent engaged in installing the power plant, distribution lines, and general plant layout. In 1919 he went with the Sinclair Refining Company at Coffeyville, Kan., as electrical superintendent on the construction of the $5,000,000 oil refinery there. He remained in that location for four years, and in 1923 he covered East Chicago, Ind., and Chicago, Ill., as electrical engineer in charge of the design, supervision of purchases, installation and maintenance of all the electrical equipment of the company, including generating stations, substations, distribution and use in all of the refineries, pipe line, oil production and sea-going vessels of the Sinclair Consolidated Oil Corporation.

Albert Reinhold Alliason (A '32, M '43) professor and head of the electrical-engineering department, Wayne University, Detroit, Mich., died June 5, 1945. Professor Alliason was born May 15, 1891 in Sandwich, Ill., and received the degrees of bachelor of science in 1926 and master of science in 1927 from the University of Michigan. During World War I, 1917–19, he served as a lieutenant in the engineer corps of the United States Army Air Service, and from 1920–1926 he was instructor in automotive electrical systems at Cass High School, Detroit. In 1927 he became instructor of the department of physics and electrical engineering for the College of the City of Detroit where he remained during the evolution of the college into Wayne University, and subsequently in 1933 he was promoted to the head of the department of electrical engineering when the college of engineering was established. Professor Alliason was credited with being the inventer of the vernier radio dial, and was a member of the Engineering Society of

Detroit and of the Society for the Promotion of Engineering Education. He was also a member of the Engineers' Council for Professional Development, serving on the national committee on student selection and guidance. He was at one time on the staff of the board of directors of the AIEE Michigan Section.

Clyde Larselere Chatham (A '25, M '32) assistant division superintendent, electric distribution department, Public Service Electric and Gas Company, Paterson, N. J., died suddenly on June 7, 1945, a few days before he was to take over the superintendency of the Passaic division. Born February 16, 1901 at Williamsport, Pa., Mr. Chatham received the degrees of bachelor of science in 1921 and master of science in 1922 in electrical engineering, from the Massachusetts Institute of Technology. Previous to graduation he gained early experience with the Bell Telephone Company of Pennsylvania, at Williamsport, and in the Lynn (Mass.) works of the General Electric Company. In 1921 he was employed as electrician for the New York and Pennsylvania Paper Company, Lock Haven, Pa., and in 1922 he became cadet engineer with the Public Service Electric and Gas Company, and subsequently was promoted to engineer of the Passaic division, electric distribution department. He was later made assistant division superintendent. Mr. Chatham was at one time a member and served on a subcommittee of the National Electric Light Association, and as a result of his investigations and research several technical reports were published.

Harry Charles Frank (M '41) research engineer, high-tension laboratories, General Cable Corporation, Bayonne, N. J., died June 9, 1945. Born February 13, 1892, in Newark, N. J., Mr. Frank received the degrees of bachelor of science from Cooper Union in 1917 and master of science from the Stevens Institute of Technology in 1932. In 1908 he was engaged as a laboratory assistant with the Weston Electrical Instrument Company, Newark, N. J., and in 1910 became associated with the New York Edison Company (N. Y.), in the maintenance of the company's primary and secondary electrical standards of measurement. In 1916 he was in the employ of the Public Service Commission for the state of New York as a junior electrical engineer, and in 1920 accepted the position as instructor of physics at the Stevens Institute of Technology, subsequently becoming assistant professor of physics in 1924. He entered the industrial field again in 1939 when he became associated with General Cable Corporation, engaged in research on high-voltage power cables in the company's research laboratory. Mr. Frank was a member of the American Physical Society, the American Physics Teachers, and the Society for the Promotion of Engineering Education.

Adolf Alfred Julius Westman (A '07, M '20) electrical engineer, Montreal, (Quebec, Canada) Tramways Company, died June 22, 1945. Born June 23, 1877, Mr. Westman received his education at the Northern Latin College, Stockholm, Sweden. In 1904 he entered the employ of the New York (N. Y.) Edison Company as electrical draftsman in the distribution department, and in 1907 he resigned from that company to accept a position with the General Electric Company, Schenectady, N. Y., as electrical designer. In 1910 he became associated with the electrical department of the New York, New Haven, and Hartford Railroad Company, New Haven, Conn., and three years later in 1913 he was serving as electrical designer for the J. G. White and Company, New York, N. Y. In 1914 he left that company to work in a similar capacity for the Montreal Public Service Corporation. In 1917 Mr. Westman was transferred to the Montreal Tramways Company as electrical engineer. He was a member of the Quebec Professional Engineers.

MEMBERSHIP . . .

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objecting to the election of any of these candidates should so inform the secretary before October 15, 1945 or December 15, 1945, if the applicant resides outside of the United States or Canada.

To Grade of Member

Armiger, C. F., City of Baltimore, Baltimore, Md.
Bladen, A. M., Neiler, Rich & Bladen, Chicago, Ill.
Champagne, L. J., Sperry Gyroscope Co., Inc., Boston, Mass.
Chin, L. Q. H. (Re-election), Westinghouse Intl. Co., New York, N. Y.
Crow, G. L., Gen. Elec. Co., Schenectady, N. Y.
Davis, L. B. (Re-election), Chesapeake & Potomac Tel. Co., Washington, D. C.
Elliott, M. B. (Re-election), Gen. Elec. Co., Schenectady, N. Y.
Elphick, J. F., Winchester Elect. Dept., Winchester, England
Gnauck, R. E., Lt. Cmdr., U.S.N.R., Washington, D. C.
Grant, H. H., Jr., Key System, Oakland, Calif.
Hoge, H., Clark Cont. Co., Cleveland, Ohio
Horbach, S., Operations Branch, Army Comm. Serv., Philadelphia, Pa.
Howard, J. G. (Re-election), Koppers Co., Inc., Pittsburgh, Pa.
Ishler, K. H., Penna. Elec. Co., Erie, Pa.
Mackintosh, D. C., Gen. Elec. Co., Schenectady, N. Y.
McCulley, J. A., Wheeling Elec. Co., Wheeling, W. Va.
Morgan, J. T. (Re-election), Charleston Elec. Sup. Co., Charleston, W. Va.
Morwood, J. E. (Re-election), Brisbane City Council, Brisbane, Australia
Nix, G. L., Kellex Corp., Knoxville, Tenn.
Payman, H. S., A. B. Metal Products, Ltd., Feltham, England
Peacock, F. E., Erik Floor & Associates, Chicago, Ill.
Phelps, G. H., Westinghouse Elec. Corp., Baltimore, Md.
Roberts, C. F., Jr. (Re-election), Major, U. S. Army, Fort Bragg, N. C.
Skaglund, H. A., Lear, Inc., Hollywood, Calif.
Skrotzki, B. G., McGraw-Hill Pub. Co., New York, N. Y.
Twomey, R. G., Tenn. Val. Auth., Chattanooga, Tenn.
Wilson, P. J. (Re-election), Walsh-Kaiser Co., Providence, R. I.

27 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Barton, R., Gen. Elec. Co., Lynn, Mass.
Berig, L., Boston Elev. Ry., Boston, Mass.
Craig, D. E., Gen. Elec. Co., Schenectady, N. Y.

2. Middle Eastern

Bennet, W. R., Westinghouse Elec. Corp., Lima, Ohio
Chesley, C. W., Charleston Elec. Sup. Co., Charleston, W. Va.
Clay, M. R., Semet Solvay Co., Longacre, W. Va.
Fasel, W. G., Penna. Elec. Co., Erie, Pa.
Hatch, C. B., Amer. Tel. & Tel. Co., Charleston, W. Va.
Henderson, W. D., U. S. Navy Dept., Washington, D. C.
Higgins, A. T., Lt. Cmdr., Naval Air Station, Lakehurst, N. J.
Hunn, R. J., E. I. du Pont de Nemours & Co., Inc., Wilmington, Del.
Hunsinger, G. O., Natl. Elec. Prod. Corp., Ambridge, Pa.
Keer, W. A., Struthers Dunn, Inc., Philadelphia, Pa.
Long, C. C., Amer. Tel. & Tel. Co., Charleston, W. Va.
Meusdorffer, R., Robbins & Myers, Inc., Springfield, Ohio
Moore, R. V., Lt. Cmdr., R.N., British Adm. Del., Washington, D. C.
Price, H. W., Jr., Bendix Radio, Towson, Md.
States, J. H., Natl. Elec. Prod. Corp., Ambridge, Pa.
Thompson, R. J., Cleve. Elec. Illumg. Co., Cleveland, Ohio
Williams, F., Firestone Tire & Rubber Co., Akron, Ohio
Zirm, R. R., U. S. Naval Res. Lab., Washington, D. C

3. New York City

Cissel, F. G., Smith, Hinchman & Grylls, New York N. Y.
Kaszychi, J., Lt. (jg), U. S. Navy, New York, N. Y.
Levine, B., Bendix Avia. Corp., Brooklyn, N. Y.
Monahan, T. I., U. S. Navy Yard, Brooklyn, N. Y.

4. Southern

Brady, G. R., Jr., Ingalls Shipbldg. Corp., Decatur, Ala.
Riley, G., Ala. Pr. Co., Birmingham, Ala.

5. Great Lakes

Brown, F. H., Pub. Serv. Co. of Northern Ill., Chicago, Ill.
dePool, N. S., Detroit Edison Co., Detroit, Mich.
Girard, J. P., Jr., Allis-Chalmers Mfg. Co., Milwaukee, Wis.
Grosser, E. H., Jr., Commonwealth Edison Co., Chicago, Ill.
Hendrickson, M. L., Commonwealth Edison Co., Chicago, Ill.
Hernandez, V. A., Student, Tri-State Col., Angola, Ind.
Howe, H. L., Pullman-Standard Car Mfg. Co., Chicago, Ill.
James, F. P., Commonwealth Edison Co., Chicago, Ill.
Loew, G. A., Allis-Chalmers Mfg. Co., West Allis, Wis.
Odlag, J., Illinois Pr. Co., Decatur, Ill.
Pordes, F., Russel Elec. Co., Chicago, Ill.
Proper, H. B., Pub. Serv. Co. of Northern Ill., Chicago, Ill.
Quist, W. G., Minneapolis-Honeywell Reg. Co., Minneapolis, Minn.
Schmidt, E. E., Cent. Ill. Pub. Serv. Co., Springfield, Ill.
Speer, P. R. (Re-election), Ind. & Mich. Elec. Co., South Bend, Ind.
Stull, K. R., Square D Co., Milwaukee, Wis.
Swikert, C. A., Hatfield Elec. Co., South Bend, Ind.
Underwood, M. R., Indianapolis Pr. & Lt. Co., Indianapolis, Ind.
Vanderheiden, V. A., Radio Station WIBA, Madison, Wis.

6. North Central

Wallis, G. F., Colo. Fuel & Iron Corp., Pueblo, Colo.

7. South West

Deal, W. R., Captain, U. S. Army, Austin, Texas
Freeman, J. L., Remington-Arms Co., Inc., Independence, Mo.
Horrigan, W. R., Allis-Chalmers Mfg. Co., Amarillo, Texas
Jones, L. W., Kansas City Pr. & Lt. Co., Kansas City, Mo.
Lewis, R. S., Okla. Gas & Elec. Co., Oklahoma City, Okla.
Mulholland, R. A., Austin Engg. Co., Austin, Texas

8. Pacific

Crouch, A. E., Dept. of Pub. Works, San Diego, Calif.
Hubbard, L. W., Jr., North Amer. Avia., Inc., Inglewood, Calif.
Kubias, F. F., Gen. Elec. Co., Los Angeles, Calif.
LaZelle, L. L., U. S. Navy Radio & Sound Lab., San Diego, Calif.
Liles, R. R., United Engg. Co., Ltd., Alameda, Calif.
Marsden, R. W., United Engg. Co., Ltd., Alameda, Calif.
Nutter, L. D., Jr., Austin Co., Pittsburg, Calif.
Spalding, R. H., Jr., U. S. Navy, San Francisco, Calif.
Teach, C. L., Lieut., U.S.N.R., San Francisco, Calif.

9. North West

Bucholz, C. S., E. I. du Pont de Nemours & Co., Inc., Richland, Wash.
Hargreaves, P. F., Puget Sound Pr. & Lt. Co., Seattle, Wash.
Weller, R. I., Guy F. Atkinson Co., Seattle, Wash.
White, D. C., Oreg. Shipbldg., Corp., Portland, Oreg.

10. Canada

Haacke, E. M., "Electrical News & Engineering," Toronto, Ont., Can.

Elsewhere

Banerjee, B. N., Tata Iron & Steel Co., Ltd., Tatanagar, India
Flashman, J. S., Elect. Lt., R.N.V.R., London, England
Goebich, A., U. S. Engineers Office, Oahu, T. H.
Howard, H. J., British Elec. & Allied Mfgrs. Assn., London, England
Majumdar, D., Keymer, Bagshawe & Co., Ltd., Calcutta, India
Meredith, A. E., ICI (Metals), Ltd., Birmingham, England
Rao, K. S., Praga Tools Corp., Ltd., Hyderabad, India

Total to grade of Associate

United States and Canada, 67

Elsewhere, 7

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W. G. Dow, *secretary*, Radio Research Laboratory, Harvard University, Cambridge, Mass.

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Robert D. Evans	S. J. Rosch
J. M. Gaylord	F. E. Sanford
I. W. Gross	R. V. Sanford
Herman Halperin	E. V. Sayles
Edwin Hansson	S. E. Schultz
K. E. Hapgood	A. E. Silver
E. R. Hendrickson	F. V. Smith
J. E. Hobson	E. C. Starr
J. B. Hodtum	O. W. Titus
E. K. Huntington	J. J. Torok
H. E. Kent	H. M. Trueblood
A. H. Kidder	C. F. Wagner
A. A. Kroneberg	Loyd T. Williams
W. W. Lewis	H. E. Wulfing

Protective Devices

H. E. Strang, *chairman*, General Electric Company, 1 River Road, Schenectady 5, N. Y.

H. W. Collins, *vice-chairman*, Detroit Edison Company, 2000 Second Ave., Detroit 26, Mich.

H. D. Braley, *secretary*, Consolidated Edison Co. of New York, Inc., 4 Irving Place, New York 3, N. Y.

O. E. Charlton	F. R. Longley
William Deans	J. R. North
H. W. Haberl	H. V. Nye
W. A. Lewis	H. H. Rudd
H. J. Lingal	W. J. Rudge

J. H. Vivian

Institute Representatives

Asronautical Electrical Equipment Standardization
J. R. North, Liaison Representative with NASC and SAE

Alfred Noble Prize Committee, ASCE
Robin Beach

American Association for the Advancement of Science, Council
T. H. Morgan — I. Melville Stein

American Committee on Marking of Obstructions to Air Navigation
J. W. Campbell — I. W. Gross

American Coordinating Committee on Corrosion
H. S. Phelps — E. B. King, *alternate*

American Research Committee on Grounding
C. T. Sinclair

American Standards Association, Standards Council
R. T. Henry — J. R. North — H. S. Osborne
Alternates
H. E. Farrer — E. B. Paxton — J. J. Pilliod

American Standards Association, Board of Directors
J. T. Barron

American Year Book, Advisory Board
H. H. Henline

Committee of Apparatus Makers and Users, NRC
L. F. Adams

Charles A. Coffin Fellowship and Research Fund Committee
W. E. Wickenden

Consultative Committee on Engineering (Advisory to the War Manpower Commission)
John Castlereagh Parker

Electrical Standards Committee, ASA
A. C. Monteith — J. R. North — J. J. Pilliod
Alternates
H. E. Farrer — E. L. Moreland — E. B. Paxton

Engineering Foundation Board
L. W. Chubb — F. M. Farmer

(*Continued on next page*)

Geographical District Executive Committees

District	Chairman (Vice-President, AIEE)	Secretary (District Secretary)	Chairman, District Committee on Student Activities (1944–45)
1 North Eastern	R. T. Henry, 303 Electric Bldg., Buffalo, N. Y.	Victor Siegfried, American Steel & Wire Co., Worcester 7, Mass.	R. G. Porter, Northeastern University, Boston, Mass.
2 Middle Eastern	E. S. Fields, Cincinnati Gas & Electric Co., 4th & Main Sts., Cincinnati, Ohio	A. A. Johnson, Westinghouse Electric Corporation, East Pittsburgh, Pa.	P. X. Rice, Pennsylvania State College, State College, Pa.
3 New York City	J. F. Fairman, Consolidated Edison Co. of New York, Inc., 4 Irving Place, New York 3, N. Y.	C. S. Purnell, Westinghouse Electric Corporation, 40 Wall St., New York 5, N. Y.	D. H. Wright, Pratt Institute, Brooklyn, N. Y.
4 Southern	H. B. Wolf, Duke Power Company, Charlotte 1, N. C.	C. B. Galphin, 2312 Greenway, Charlotte 4, N. C.	W. O. Leffell, University of Tennessee, Knoxville, Tenn.
5 Great Lakes	M. S. Coover, Iowa State College, Ames, Iowa	N. C. Pearcy, Public Utilities Engg. & Service Corp., 231 S. LaSalle St., Chicago 4, Ill.	M. M. Cory, Michigan State College, East Lansing, Mich.
6 North Central	L. M. Robertson, Public Service Co. of Colorado, Denver, Colo.	H. F. Gidlund, Public Service Co. of Colorado, Denver, Colo.	O. E. Edison, University of Nebraska, Lincoln, Nebr.
7 South West	R. W. Warner, University of Texas, Austin, Tex.	S. R. Friedsam, 3612 Bonnie Road, Austin, Tex.	M. C. Hughes, A. & M. College of Texas, College Station, Tex.
8 Pacific	F. F. Evenson, 600 E. Harbor St., P. O. Box 1710, San Diego, Calif.	Walter L. Bryant, Univ. of Calif. Div. of War Research, U. S. Navy Radio & Sound Laboratory, San Diego 52, Calif.	F. W. Maxstadt, California Institute of Technology, Pasadena, Calif.
9 North West	C. B. Carpenter, Pacific Tel. & Tel. Co., 730 S. W. Oak St., Portland 5, Oreg.	C. C. Boozier, Westinghouse Electric Corporation, 309 S. W. Sixth Ave., Portland 4, Oreg.	L. D. Harris, University of Utah, Salt Lake City, Utah
10 Canada	F. L. Lawton, Aluminum Co. of Canada Ltd., 1700 Sun Life Bldg., Montreal, Que.	D. M. Farnham, Quebec Hydro-Elec. Commission, 107 Craig St. West, Montreal, Que.	

NOTE: Each District executive committee includes also the chairmen and secretaries of all Sections within the District, and the District vice-chairman of the AIEE membership committee.

Institute Representatives (continued)

Engineering Societies Monographs Committee
F. M. Farmer — W. I. Slichter

Engineering Societies Personnel Service, Inc.
H. H. Henline

Engineers' Council for Professional Development
O. W. Eshbach — Everett S. Lee — E. C. Stone

Hertz Award Committee
M. S. Coover

Hoover Medal Board of Award
H. H. Barnes, Jr. — F. M. Farmer — John C. Parker

John Fritz Medal Board of Award
Nevin E. Funk — C. A. Powel
H. S. Osborne — David C. Prince

Joint Conference Committee of Founder Societies and A.I.Ch.E.
H. H. Henline — C. A. Powel — W. E. Wickenden

Library Board, United Engineering Trustees, Inc.
H. H. Henline — G. L. Knight
N. S. Hibshman — W. I. Slichter

Marston Medal Board of Award
H. B. Gear

National Bureau of Engineering Registration, Advisory Board
C. R. Beardsley

National Fire Protection Association, Electrical Committee
L. F. Adams — W. Ralph Smith, *alternate*

National Fire Waste Council
L. F. Adams — Wills Maclachlan

National Research Council, Division of Engineering and Industrial Research
Wm. B. Kouwenhoven

Quarterly of Applied Mathematics
J. G. Brainerd

Radio Technical Planning Board
H. A. Affel

Research Procedure Committee, Engineering Foundation
W. A. Lewis

United Engineering Trustees, Inc.
F. M. Farmer — C. R. Jones — Everett S. Lee

U. S. National Commission, International Commission on Illumination
J. W. Barker — Robin Beach — S. G. Hibben

U. S. National Committee, International Electrotechnical Commission
A. C. Monteith — J. R. North — J. J. Pilliod
Alternates:
H. E. Farrer — E. L. Moreland — E. B. Paxton

Washington Award Commission
H. B. Gear — L. R. Maple

World Power Conference, Executive Committee of
W. L. Wickenden — U. S. National Committee

General Counsel

Parker & Aaron, 55 Liberty Street, New York 5, N. Y.

Student Branches of the Institute

Name and Location	District	Counselor (Member of Faculty)
Akron, Univ. of, Akron, Ohio	2	
Alabama Polytechnic Inst., Auburn	4	
Alabama, Univ. of, University	4	W. J. Miller
Alberta, Univ. of, Edmonton, Can.	10	R. E. Phillips
Arizona, Univ. of, Tucson	8	J. C. Clark
Arkansas, Univ. of, Fayetteville	7	W. B. Stelzner
British Columbia, Univ. of, Vancouver, Can.	10	
Brooklyn, Polytechnic Inst. of, Brooklyn, N. Y.	3	A. B. Giordano
Brown University, Providence, R. I.	1	
Bucknell Univ., Lewisburg, Pa.	2	
Calif. Inst. of Tech., Pasadena	8	W. H. Pickering
Calif. Univ. of, Berkeley	8	P. L. Morton
Carnegie Inst. of Technology, Pittsburgh, Pa.	2	
Case School of Applied Science, Cleveland, Ohio	2	
Catholic Univ. of America, Washington, D. C.	2	
Cincinnati, Univ. of, Cincinnati, Ohio	2	
Clarkson College of Technology, Potsdam, N. Y.	1	
Clemson Agricultural College, Clemson, S. C.	4	F. T. Tingley
Colorado State Col. of A. & M. Arts, Fort Collins	6	F. B. Beatty
Colorado, Univ. of, Boulder	6	Platt Wicks
Columbia Univ., New York, N. Y.	3	W. A. LaPierre
Connecticut, Univ. of, Storrs	1	
Cooper Union, New York, N. Y.	3	E. E. Shelton
Cornell Univ., Ithaca, N. Y.	1	
Delaware, Univ. of, Newark, Del.	2	
Denver, Univ. of, Denver, Colo.	6	F. H. McClain
Detroit, Univ. of, Detroit, Mich.	5	H. O. Warner
Drexel Inst. of Technology, Philadelphia, Pa.	2	
Duke Univ., Durham, N. C.	4	Otto Meier, Jr.
Florida, Univ. of, Gainesville	4	E. F. Smith
George Washington Univ., Washington, D. C.	2	
Georgia School of Technology, Atlanta, Ga.	4	H. B. Duling
Harvard Univ., Cambridge, Mass.	1	J. P. Newton
Idaho, Univ. of, Moscow, Idaho	9	J. Hugo Johnson
Illinois Inst. of Technology, Chicago, Ill.	5	E. H. Freeman
Illinois, Univ. of, Urbana	5	E. A. Reid
Iowa State Col., Ames	5	B. S. Willis
Iowa, Univ. of, Iowa City	5	H. R. Reed
Johns Hopkins Univ., Baltimore, Md.	2	
Kansas State Col., Manhattan	7	R. G. Kloeffler
Kansas, Univ. of, Lawrence	7	G. A. Richardson
Kentucky, Univ. of, Lexington	4	Brinkley Barnett
Lafayette Col., Easton, Pa.	2	
Lehigh Univ., Bethlehem, Pa.	2	
Louisiana State Univ., Baton Rouge	4	M. B. Voorhies
Louisville, Univ. of, Louisville, Ky.	4	M. C. Northrup
Maine, Univ. of, Orono	1	
Manhattan Col., New York, N. Y.	3	R. T. Weil
Marquette Univ., Milwaukee, Wis.	5	E. W. Kane
Maryland, Univ. of, College Park	2	
Mass. Inst. of Technology, Cambridge 39	1	
Michigan Col. of Mining & Tech., Houghton	5	G. W. Swenson
Michigan State Col., East Lansing	5	M. M. Cory
Michigan, Univ. of, Ann Arbor	5	J. S. Gault
Milwaukee School of Engg., Milwaukee, Wis.	5	E. L. Wiedner
Minnesota, Univ. of, Minneapolis	5	J. H. Kuhlmann
Mississippi State Col., State College	4	L. L. Patterson
Missouri School of Mines & Met., Rolla	7	F. H. Frame
Missouri, Univ. of, Columbia	7	M. P. Weinbach
Montana State Col., Bozeman	9	E. W. Schilling
Nebraska, Univ. of, Lincoln	6	O. E. Edison
Nevada, Univ. of, Reno	8	S. G. Palmer
Newark Col. of Engineering, Newark, N. J.	3	J. C. Peet
New Hampshire, Univ. of, Durham	1	
New Mexico State College, State College	7	H. A. Brown
New Mexico, Univ. of, Albuquerque	7	R. W. Tapy
New York, Col. of the City of, New York	3	Hairy Baum
New York Univ., New York	3	P. C. Cromwell
North Carolina State Col., Raleigh	4	L. M. Keever
North Dakota State Agri. Col., Fargo	5	H. S. Rush
North Dakota, Univ. of, Grand Forks	5	C. W. Rook
Northeastern Univ., Boston, Mass.	1	
Northwestern Univ., Evanston, Ill.	5	R. Beam
Norwich Univ., Northfield, Vt.	1	
Notre Dame Univ. of, Notre Dame, Ind.	5	J. A. Northcott
Ohio Northern Univ., Ada	2	
Ohio State Univ., Columbus	2	
Ohio University, Athens	2	
Oklahoma A. & M. College, Stillwater	7	A. Nacter
Oklahoma, Univ. of, Norman	7	C. L. Farrar
Oregon State Col., Corvallis	9	A. L. Albert
Pennsylvania State Col., State College	2	
Pennsylvania, Univ. of, Philadelphia	2	
Pittsburgh, Univ. of, Pittsburgh, Pa.	2	
Pratt Institute, Brooklyn, N. Y.	3	D. H. Wright
Princeton Univ., Princeton, N. J.	2	
Puerto Rico, Univ. of, Mayaguez, P. R.	3	M. Wiewall, Jr.
Purdue Univ., Lafayette, Ind.	5	R. B. Marshall
Rensselaer Polytechnic Inst., Troy, N. Y.	1	
Rhode Island State Col., Kingston, R. I.	1	
Rice Institute, Houston, Texas	7	M. V. McEnaney
Rose Polytechnic Inst., Terre Haute, Ind.	5	C. C. Knipmeyer
Rutgers Univ., New Brunswick, N. J.	3	P. S. Creager
Santa Clara, Univ. of, Santa Clara, Calif.	8	W. J. Warren
South Carolina, Univ. of, Columbia	4	Samuel Litman
South Dakota State Col., Brookings	5	W. H. Gamble
South Dakota State School of Mines, Rapid City	6	E. E. Clark
Southern California, Univ. of, Los Angeles, Calif.	8	P. S. Biegler
Southern Methodist Univ., Dallas, Texas	7	R. L. Biesele, Jr.
Stanford Univ., Stanford University, Calif.	8	H. H. Skilling
Stevens Inst. of Technology, Hoboken, N. J.	3	W. L. Sullivan
Swarthmore Col., Swarthmore, Pa.	2	
Syracuse Univ., Syracuse, N. Y.	1	
Tennessee, Univ. of, Knoxville	4	J. G. Tarboux
Texas A. & M. Col., College Station	7	M. C. Hughes
Texas Tech. Col., Lubbock, Texas	7	W. F. Helwig
Texas, Univ. of, Austin	7	A. W. Straiton
Tufts College, Medford, Mass.	1	
Tulane Univ., New Orleans 15, La.	4	M. G. Zervigon
Union Col., Schenectady 5, N. Y.	1	
Utah, Univ. of, Salt Lake City	9	C. C. Haycock
Vanderbilt Univ., Nashville, Tenn.	4	S. R. Schealer
Vermont, Univ. of, Burlington	1	
Villanova Col., Villanova, Pa.	2	
Virginia Military Inst., Lexington, Va.	4	J. S. Jamison
Virginia Polytechnic Inst., Blacksburg	4	Claudius Lee
Virginia, Univ. of, Charlottesville, Va.	4	L. R. Quarles
Washington, State College of, Pullman	9	H. F. Lickey
Washington, Univ. of, Seattle	9	R. E. Lindblom
Washington Univ., St. Louis, Mo.	7	D. A. Fischer
West Virginia Univ., Morgantown	2	
Wisconsin, Univ. of, Madison	5	G. F. Tracy
Worcester Polytechnic Inst., Worcester, Mass.	1	
Wyoming, Univ. of, Laramie	6	R. O. Trueblood
Yale University, New Haven, Conn.	1	
Total Branches	125	

Local Sections of the Institute

Name	District	When Organized	Membership Aug. 1, 1945	Chairman	Secretary	Secretary's Address
Akron	2	Aug. 12, '20	105	M. B. Rankin	F. J. Ilse	795 West Market St., Akron 3, Ohio
Alabama	4	May 22, '29	37	F. C. Weiss	Robert S. Morrison	Westinghouse Electric Corp., 1406 Comer Bldg., Birmingham 3, Ala.
Arizona	8	Mar. 22, '41	60	Charles A. Rollins	E. A. Gisel	Central Arizona Light & Power Co., Phoenix, Ariz.
Beaumont	7	June 27, '45	61	Harold McIntosh	N. C. Spencer	2555 North St., Beaumont, Texas
Boston	1	Feb. 13, '03	673	F. S. Bacon, Jr.	R. E. Muehlig	Westinghouse Electric Corp., 235 Old Colony Ave., Boston, Mass.
Central Indiana	5	Jan. 12, '12	147	S. C. Leibing	E. G. Hinshaw	Indiana Bell Telephone Co., 240 N. Meridian St., Indianapolis, Ind.
Chicago	5	1893	959	J. F. Calvert	L. R. Janes	Public Service Co. of Northern Ill., 72 West Adams St., Chicago 3, Ill.
Cincinnati	2	June 30, '20	161	F. W. Willey	Paul R. Goodell	4817 Section Avenue, Cincinnati 12, Ohio
Cleveland	2	Sept. 27, '07	423	V. A. Diggs	R. W. Loehr	Westinghouse Electric Corp., 1216 West 58th St., Cleveland 1, Ohio
Columbus	2	Mar. 17, '22	90	N. J. Greene	O. E. Holzer	397 Acton Rd., Columbus 2, Ohio
Connecticut	1	Apr. 16, '21	384	Vincent J. Hayes	Elmer G. Horton	Westinghouse Electric Corp., P. O. Box 1817, New Haven 8, Conn.
Dayton	2	June 9, '43	243	F. S. Himebrook	W. A. Dynes	312 Lonsdale Ave., Dayton 9, Ohio
Denver	6	May 18, '15	209	Louis A. Goalby	Leroy R. Patterson	Public Service Co. of Colorado, Denver, Colo.
East Tennessee	4	Sept. 2, '36	288	C. P. Almon, Jr.	S. E. Lyons	Tennessee Valley Authority, Power Bldg., Chattanooga, Tenn.
Erie	2	Jan. 11, '18	73	Harold S. Ogden	Wilbur C. Brown	General Electric Co., East Lake Road, Erie, Pa.
Florida	4	Jan. 28, '31	125	P. J. Carlin	C. H. Summers	Florida Power & Light Co., Miami, Fla.
Fort Wayne	5	Aug. 14, '08	107	E. G. Downie	L. L. Ray	General Electric Co., 1635 Broadway, Fort Wayne 2, Ind.
Georgia	4	Jan. 14, '04	145	Carl W. Evans	Robert O. Loomis	Georgia Power Co., Atlanta 1, Ga.
Houston	7	Aug. 7, '28	143	S. C. Commander	H. Lee Miller	Houston Lighting & Power Co., P. O. Box 1700, Houston 1, Texas
Illinois Valley	5	June 30, '45	47	F. E. Dace	R. P. Johnson	2511 W. Forrest Hill Ave., Peoria 5, Ill.
Iowa	5	June 29, '29	85	John A. Green	Wallace L. Cassell	Iowa State College, Ames, Iowa
Ithaca	1	Oct. 15, '02	72	N. L. Platt	W. H. Erickson	School of Elec. Engg., Cornell University, Ithaca, N. Y.
Kansas City	7	Apr. 14, '16	149	A. F. Hartung	J. E. Murray	J. E. Murray & Co., 1805 Grand Ave., Kansas City 8, Mo.
Lehigh Valley	2	Apr. 16, '21	188	L. Z. Ludorf	A. L. Price	173 South Church St., Hazleton, Pa.
Los Angeles	8	May 19, '08	718	Earl S. Condon	H. D. Strong	General Electric Co., P. O. Box 2830 Terminal Annex, Los Angeles 54, Calif.
Louisville	4	Oct. 15, '24	75	S. H. Gates	L. W. Anderson	647 Starks Bldg., Louisville 2, Ky.
Lynn	1	Aug. 22, '11	210	C. B. Fontaine, Jr.	Mark A. Princi	19 Clifton Ave., Marblehead, Mass.
Madison	5	Jan. 8, '07	81	J. A. Roller	Carl C. Crane	3810 Council Crest, Madison 5, Wis.
Mansfield	2	Mar. 6, '39	63	C. L. Lisle	H. E. Edwards	Westinghouse Electric Corp., Mansfield, Ohio
Maryland	2	Dec. 16, '04	417	J. L. Hildebrandt	Edwin Hannon	Penn. Water & Power Co., 1409 Lexington Bldg., Baltimore 1, Md.
Memphis	4	May 22, '30	94	J. A. Crisman	W. R. Moyers, Jr.	3480 Macon Rd., Memphis, Tenn.
Mexico	3	June 29, '22	181	F. A. Nava	Oscar R. Enriquez	Ave. Chapultepec 281-6, Mexico, D. F. Mexico
Michigan	5	Jan. 13, '11	436	L. W. Clark	G. M. Chute	General Electric Co., 700 Antoinette St., Detroit 2, Mich.
Milwaukee	5	Feb. 11, '10	408	G. W. Clothier	E. T. Sherwood	Globe Union, Inc., 900 E. Keefe Ave., Milwaukee 1, Wis.
Minnesota	5	Apr. 7, '02	133	Leroy A. Griffith	John H. Merriman	Northern States Power Co., 15 South St., Minneapolis 2, Minn.
Montana	9	June 24, '31	71	F. E. Gardiner	E. W. Williams	715 W. Galena St., Butte, Montana
Montreal	10	Apr. 16, '43	237	John J. Dougherty	Harold H. Remine	Quebec Hydro Elec. Commission, Montreal, Que., Canada
Muscle Shoals	4	Feb. 18, '38	19	W. E. Lindemann	Ernest L. Bishop	76 F St., Village 1, Wilson Dam, Ala.
Nebraska	6	Jan. 21, '25	48	M. L. Burgess	I. M. Ellestad	Northwestern Bell Tel. Co., Omaha, Neb.
New Mexico-West Texas	7	Mar. 7, '40	57	Robert C. Dickson	John F. Armstrong	3219 Altura Blvd., El Paso, Texas
New Orleans	4	Dec. 8, '33	159	Wm. Stone Leake	S. L. Kennedy	Louisiana Power & Light Co., Metairie, La.
New York	3	Dec. 10, '19	3,949	J. L. Callahan	W. J. Barrett	New Jersey Bell Telephone Co., 540 Broad St., Newark 2, N. J.
Niagara Frontier	1	Feb. 10, '25	198	J. M. Geiger	John D. Hershey	General Electric Co., 1 West Genesee St., Buffalo 2, N. Y.
North Carolina	4	Mar. 21, '29	137	Otto Meier, Jr.	J. O. Emery	Duke Power Co., 112 North Mangum St., Durham, N. C.
North Texas	7	May 18, '28	199	R. W. Roesler	H. K. Doyle	Dallas Power & Light Co., Dallas, Texas
Oklahoma City	7	Feb. 16, '22	109	W. A. Kitchen	H. E. Brashear	Southwestern Bell Tel. Co., Oklahoma City, Okla.
Philadelphia	2	Feb. 18, '03	925	C. T. Pearce	W. R. Clark	Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia 44, Pa.
Pittsburgh	2	Oct. 13, '02	693	C. M. Skoglund	J. B. Hodnum	Allis-Chalmers Mfg. Co., N. S. Station, Pittsburgh 12, Pa.
Pittsfield	1	Mar. 25, '04	201	M. E. Scoville	J. C. Russ	Power Transformer Engg. Dept., General Electric Co., Pittsfield, Mass.
Portland	9	May 18, '09	228	O. A. Demuth	W. Morgan Allen	Pacific Tel. & Tel. Co., 730 S. W. Oak St., Portland, Oreg.
Providence	1	Mar. 12, '20	104	Donald E. Walch	George E. Andrews	Narragansett Electric Co., Melrose St., Providence, R. I.
Rochester	1	Oct. 9, '14	133	Ernest B. Kempster	George R. Town	Stromberg-Carlson Co., 100 Carlson Rd., Rochester 3, N. Y.
St. Louis	7	Jan. 14 '03	346	Harry B. Seybt	R. C. Horn	1820 Telephone Bldg., 1010 Pine St., St. Louis 1, Mo.
San Diego	8	Jan. 18, '39	102	R. R. Richey	G. E. Jenner	861 Sixth St., San Diego 12, Calif.
San Francisco	8	Dec. 23, '04	776	D. I. Anzini	H. E. Becker	Westinghouse Electric Corp., 1 Montgomery St., San Francisco 4, Calif.
Schenectady	1	Jan. 26, '03	654	P. H. Light	B. H. Caldwell	Motor & Gen. Engg. Div., General Electric Co., Schenectady 5, N. Y.
Seattle	9	Jan. 19, '04	303	E. B. Hansen	George M. Palo	1707 Bigelow Ave. North, Seattle 9, Wash.
Sharon	2	Dec. 11, '25	149	A. D. Forbes	C. W. Miller	840 Mayfield Rd., Sharpsville, Pa.
South Bend	5	Feb. 26, '41	70	C. D. Highleyman	John C. Learman	1245 North Meade St., South Bend, Ind.
South Carolina	4	Mar. 2, '40	56	F. T. Tingley	J. L. Weeks	South Carolina Elec. & Gas Co., Columbia, S. C.
South Texas	7	May 23, '30	56	N. Bernard Gussett	Robert M. Eichner	General Electric Co., 1014 Transit Tower, San Antonio, Texas
Spokane	9	Feb. 14, '13	106	J. F. Gogins	R. R. Ries	1528 West Augusta, Spokane 12, Wash.
Springfield	1	June 29, '22	60	Byron N. Durfee	Fred G. Webber	9 Federal Court, Springfield, Mass.
Syracuse	1	Aug. 12, '20	149	C. E. H. Von Sothen	L. J. Audlin	Central N. Y. Power Corp., 300 Erie Blvd. West, Syracuse 2, N. Y.
Toledo	2	June 3, '07	67	F. G. Helwig	Walter M. Campbell	2145 Central Grove Ave., Toledo, Ohio
Toronto	10	Dec. 30, '03	400	H. F. Thompson	J. H. Munro	Dunlop Wire & Cable Goods, 670 Queen St., E., Toronto, Ont., Canada
Tulsa	7	Oct. 1, '37	81	P. E. Gentry	L. F. Rylander	Public Service Co. of Oklahoma, 600 So. Main St., Tulsa, Okla.
Urbana	5	Nov. 25, '02	38	E. A. Reid	C. A. Keener	308 Elec. Engg. Lab., University of Illinois, Urbana, Ill.
Utah	6	Mar. 9, '17	77	L. Dale Harris	John A. McDonald	General Electric Co., P. O. Box 779, Salt Lake City, Utah
Vancouver	10	Aug. 22, '11	109	J. D. Fraser	G. K. Haspel	1992 41st Ave., West, Vancouver, B. C., Canada
Virginia	4	May 19, '22	136	J. A. Rawls	C. H. Smoke	1523 Holland Ave., Norfolk 5, Va.
Washington	2	Apr. 9, '03	726	E. T. Walker	L. H. Cleary	1022 20th St. N. W., Washington 6, D. C.
West Virginia	2	Apr. 9, '40	50	W. E. Vellines, Jr.	R. F. Norwood	1400 Bridge Road, Charleston 3, West Virginia
Wichita	7	Sept. 16, '37	86	H. Kenneth Hentzen	Hugh E. Hartman	Kansas Gas & Electric Co., 201 N. Market St., Wichita 1, Kans.
Worcester	1	Feb. 18, '20	59	A. L. Duna	G. W. Bibber	Heald Machine Co., New Bond St., Worcester 6, Mass.
Total Sections	75		19,913			

Local Subsections

Arrowhead (Minnesota Section)	H. Carpenter	R. H. Holmes	Minnesota Power & Light Co., 30 W. Superior St., Duluth 2, Minn.
Charleston (South Carolina Section)	D. H. Davis	M. G. Toole	P. O. Box 23, Navy Yard, Charleston, S. C.
Great Falls (Montana Section)		D. A. Johnson	Mountain States Tel. & Tel. Co., 401 First Ave. N., Great Falls, Mont.
Hamilton (Toronto Section)	J. M. Somerville	W. J. Porter	Canadian Westinghouse Co., Hamilton, Ont., Canada.
Lake Charles (New Orleans Section)	A. D. Hargroder	G. V. Cooper	Cities Service Refining Corp., Tuttwiler Refinery, Lake Charles, La.
Niagara Falls (Niagara Frontier Section)	G. A. Zehr	C. R. Staker	203 79 St., Niagara Falls, N. Y.
Ottawa (Montreal Section)	B. G. Ballard	J. H. Simpson	National Research Council, Ottawa, Ont., Canada
Panhandle (North Texas Section)	J. G. Ausman	D. H. Hickey	Capitol Hotel, Amarillo, Texas
Rock River Valley (Madison Section)	B. T. Anderson	R. E. Schuette	Barber-Colman Co., Rockford, Ill.
Sacramento (San Francisco)	W. E. Camp	E. A. McGinty	Pacific Gas & Electric Co., 1314 29 St., Sacramento 16, Calif.
Wilmington (Philadelphia Section)	R. G. Rudrow	Henry Evans	Delaware Power & Light Co., 600 Market St., Wilmington, Del.
Zanesville (Columbus Section)	J. G. Tankovich	A. J. Baker	Ohio Power Co., Zanesville, Ohio

OF CURRENT INTEREST

Foundation to Develop Scientific Research

A National Research Foundation established by Congress for the purpose of developing scientific research, supporting financially basic research in nonprofit organizations, encouraging scientific talent in American youth by offering scholarships and fellowships, and promoting long-range research on military matters is recommended by Doctor Vannevar Bush, director of the Office of Scientific Research and Development in a report to the White House, prepared at the request of the late President Roosevelt. Urging a new impetus to scientific research in the United States, Doctor Bush stated that research cannot be left solely to private industry though private sources should continue to carry their share of the financial burden. The 184-page report entitled, "Science, The Endless Frontier," lists five divisions of the Foundation—medical research, natural sciences, national defense, scientific personnel and education, and publications and scientific collaboration.

Referring to the deficit in trained scientific personnel in the United States, Doctor Bush suggests a program to provide 24,000 undergraduate scholarships and 900 graduate fellowships at an annual cost to the Government of approximately $30,000,000. These beneficiaries would constitute a reserve, subject to call into government service, for scientific or technical work in time of war or other emergency. He claimed that the armed services should comb their records for men who, prior to or during the war, gave evidence of talent for science, and make prompt arrangements, consistent with current discharge plans, for ordering those who remain in uniform as soon as militarily possible to duty at institutions here and overseas where they can continue their scientific education.

Basic principles which must underlie the program of Government support for scientific research and education if such support is to be effective and if it is to avoid "impairing the very things we seek to foster" are enumerated as follows:

1. Whatever the extent of support may be, there must be stability of funds over a period of years so that long-range programs may be undertaken.

2. The agency to administer such funds should be composed of citizens selected only on the basis of their interest in and capacity to promote the work of the agency. They should be persons of broad interest in and understanding of the peculiarities of scientific research and education.

3. The agency should promote research through contracts of grants to organizations outside the Federal Government. It should not operate any laboratories of its own.

4. Support of basic research in the public and private colleges, universities, and research institutes must leave the internal control of policy, personnel, and the method and scope of the research to the institutions themselves.

5. While assuring complete independence and freedom for the nature, scope, and methodology of research carried on in the institutions receiving public funds, and while retaining discretion in the allocation of funds among such institutions, the Foundation proposed herein must be responsible to the President and the Congress. Only through such responsibility can we maintain the proper relationship between science and other aspects of a democratic system. The usual controls of audits, reports, budgeting and the like, should, of course, apply to the administrative and fiscal operations of the Foundation, subject, however, to such adjustments in procedure as are necessary to meet the special requirements of research.

The report, prepared under the inspirational words of President Roosevelt—"New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life," suggests legislation now declaring that early action is imperative if the United States is to meet the challenge of science and utilize to the full the potentialities of science. In the opinion of Doctor Bush the future of the United States depends upon the wisdom with which science is applied to the problems of the future.

Radio Communication for Trains

Radio equipment for use on trains, and between trains and wayside stations will be tested on the western lines of the Illinois Central Railroad between Freeport, Ill., and Waterloo, Ia., a 162-mile district chosen for the variety of operating conditions it offers, including prairie country, bluff regions, cities, river crossings, one tunnel, and curved and straight-away track. Electronic principles developed for the Armed Forces and used on planes, tanks and in ships will be utilized.

One type to be tested, space radio, is kindred to radiobroadcasting as it is heard in American homes. It will be used primarily for talking back and forth between the engine and the caboose on a freight train. Space radio operates on the high-frequency channels which were assigned recently for train use by the Federal Communications Commission. Static and noise interference common to standard broadcasting are largely absent on these high frequencies. The equipment as developed today is a simple arrangement, consisting of only a small transmitter-receiver, a remote control box with handphone, a loud-speaker and antenna on each engine and caboose. No dependence on outside electrical devices is involved for engineer-and-conductor conversation.

The second type to be tried is carrier, or induction, radio. This equipment is not radio in the ordinary sense, for it follows wayside wires and its messages are neither beamed nor broadcast. The standard wire system already along the right-of-way is used for carrier radio without interference to the present telephone and telegraph systems. The radio messages jump the space between the wires and the radio units in the train by induction. This provides continuous communication between the operator in the wayside station and the train crew in the engine cab and the caboose.

World Educational Body Formed

Dedicated to the proposition that the "free and unrestricted education of the peoples of the world, and the free and unrestricted exchange among them of ideas and knowledge are essential to the advancement of human welfare and to the preservation of security and peace," the Educational and Cultural Organization of the United Nations is to be established at the invitation of the British Government following a United Nations' conference scheduled for November 1, 1945 in London. Adopted in its present form by 20 nations which have been represented at meetings of the Allied Ministers of Education in England for the last two years, the charter pledges its support in helping to preserve security and peace. The new organization will promote international interchange in the fields of science, education, the arts, and the social sciences.

The purposes are clearly defined in Article 1. It reads as follows:

(a). To develop and maintain mutual understanding and appreciation of the life and culture, the arts, the humanities and the sciences of the peoples of the world as a basis for effective international organization and world peace.

(b). To co-operate in extending and in making available to all peoples for the service of common human needs the world's full body of knowledge and culture, and in assuring its contribution to the economic stability, political security, and general well-being of the peoples of the world.

Radar Secret Revealed

No more hush! hush! on radar, a war baby which has come of age. The uses of radar—radio detection and range—in war and in peace were revealed on August 14, 1945 both in Washington and in London. The story of this device which goes back many years has been avidly awaited since it helped the British air squadrons beat off the Germans in 1940; in 1942 when the German submarine threatened the British in their island kingdom with starvation, and more recently because of its major role in the Pacific zone of fighting.

Though radar sets vary in size depending on whether they are installed on the ground, in planes or in ships, the principle is the same—the transmitting of pulses of electromagnetic waves which hit something—an area on the ground, a plane, or a ship—and bounce back into the radar receiver forming images on a screen-like device called the "scope." These pulses travel at the speed of light, namely, 186,000 miles, a second and the range is indicated by the marked circle on the "scope" in which the target image comes to rest. The direction of the target is determined by directional antennas.

Some detailed information released by the Army on the equipment and operation of radar will be published in a forthcoming issue of *Electrical Engineering*.

General Motors Research Center Planned

Citing modern science as the real source of economic progress, Alfred P. Sloan, Jr. chairman of General Motors Corporation, New York, N. Y., recently announced the establishment of the General Motors Technical Center, which will meet tomorrow's needs for the corporation's research, advanced engineering, and styling and process development sections of its general staff activities. In making this announcement at a "More Jobs Through Research" luncheon in the Waldorf-Astoria Hotel, New York, before a representative group of scientists, educators, editors, engineers and industrialists, Mr. Sloan further declared that this new center represents long-considered plans of General Motors Corporation to expand, at the right time and on a broad scale, its peacetime research, and engineering activities.

The various buildings comprising the General Motors Technical Center will be grouped around a central esplanade within which will be a seven-acre lake which in itself fills a useful purpose in the operations of the Center. The Center will be erected on property one and one-half miles long and about half a mile wide covering approximately 350 acres, just outside of Detroit, Mich.

C. E. Wilson, president of the corporation, emphasized the fact that the new Technical Center would be purely a technical fact-finding and experimental development activity. However, by a close liaison between the Technical Center and the manufacturing divisions, executives of the divisions who have the responsibility for product development and processing can make decisions affecting their activities with greater assurance and with less loss of time.

According to Charles F. Kettering, vice president and director of research of the corporation, facilities are only a part of the story of this technical center. The more important factor had not been overlooked, namely, the men to use these new facilities—the men who can make ideas grow into material things. Mr. Kettering also said:

> General Motors has found through more than 30 years of practical experience that it cannot offer to the public many new and better things through the process of wishing. For this reason, each of its many divisions has its own product research and engineering departments. These are supplemented by a central research laboratory, advanced engineering section, styling section and process development section. In addition to these central facilities we have proving grounds at Milford, Mich., Pheonix, Ariz., and Miami, Fla. Rounding out this development background is the General Motors Institute at Flint, Mich., whose function is to train certain future General Motors employees in the use of their hands and minds.

"Unit" Power Plants Designed for Europe

Small, easily transportable power plants which can be erected in a few days to generate electric current sufficient for the needs of a city of 10,000, are being shipped to Europe to speed the return of bombed-out regions to normal industrial production, according to William E. Knox, vice president of the Westinghouse Electric International Company. Each "unitized" plant embraces the primary essentials of a modern power station—generator, steam turbine, boiler, switchgear, fuel burning equipment, piping and insulation, instruments and other parts. More than 100,000 kw of electrical energy are represented in the unit plants now in actual operation or under construction. The units are of two sizes, one with a capacity of 2,000 kw, the other half as large.

The idea of a compact power-producing unit first was conceived by Mr. Knox for use in China. The Chinese needed a quick means of generating electrical power for war-production facilities which had been forced back from the coast and deep into the interior by the advancing Japanese troops. Working in conjunction with a firm of New York engineering consultants, Westinghouse designers fulfilled the demand for equipment that would operate on locally abundant low-grade coal. Other models have been built to burn lignite, oil, wood, and even peat. While the first plants were intended for permanent erection at the ultimate site, the rapid pace of the mechanized conflict upset the engineers' timetable and called for a machine that could be put together in a minimum of time. The result was a "semi-portable design" which fulfilled the purpose, and, in addition, could be set up right on the field.

Despite the diverse climates in which these plants will be used, engineers had to allow for only two variables in the design: type and grade of fuels available; and what engineers call "ambient temperature"—the air temperature at the site of the plant.

The original intent was to relieve purchasers of equipment selection and to enable them to buy from a single source.

Culture—Aim of Proposed Curriculum

In a 267-page volume, entitled "General Education in a Free Society," a committee of Harvard University, appointed by President Conant in 1943, recommends greater emphasis on general education at all levels of instruction rather than the special education, such as vocational and trade subjects in high schools and special areas in college. General education and specialism need not be placed in competition, the report states, but it deplores the condition whereby a student receives an excellent training in chemistry, music, botany or the fine arts under an elective plan but with his general education largely neglected. Therefore, the committee recommends that a minimum of 50 per cent of a student's time be devoted to a study of general education in high school. A "core" curriculum is suggested to be built around English, science, mathematics and the social sciences. Developing a common core for all students, in the schools, it is reasoned, would help to produce more intelligent citizens for ". . . a sound society." Specific courses are suggested, designed to achieve the aims of general education and to give the students an insight into the nature of the scientific enterprise. The aim is culture for all. Doctor Paul H. Buck, dean of the faculty of arts and sciences, headed the committee of 12 who unanimously approved the findings of the two-year study.

A new program for Yale University, New Haven, Conn., resembling these proposals has been accepted.

General Electric Electronics Training Course

A new industrial-electronics talking slide-film training course which offers a practical understanding of industrial electronics, has been announced by the General Electric Company, Schenectady, N. Y. The course consists of 12 talking slide-films (35-mm film strips and 16-inch, 33⅓-rpm records) each approximately 30 minutes in length; 25 copies each of 12-lecture review booklets keyed to the slidefilms; an instructor's manual covering the presentation of all 12 lectures; and, sturdily constructed carrying case designed to accommodate the complete course. The price of the course is $100.

Commenting on the course, L. A. Umansky (M '27), assistant manager of the company's industrial engineering divisions, said that the need for a course of this kind has been sharply felt for some time. It was his belief that an explanation of the elementary facts of electronics in a simple form, readily understood by practical men, destroys the fear of the unknown and encourages them to use this new tool as freely as they used other and older electrical tools. Also, the course pointed out the "how" and "why" of electronics in industrial life; where the use of electronics would be merely a fad of a misapplication. Only in this way did he believe electronics would find its legitimate place.

Advocates Curtailing of German Industry

Conquered Germany's electrical equipment industry, still grossly expanded despite 40 per cent destruction by Allied bombs, must be trimmed to normal peacetime production levels, in the opinion of Charles A. Powel, newly appointed chief of the electrical and radio branch of the Allied Control Commission. Mr. Powel, past president AIEE has taken leave of absence from his position of headquarters engineering manager for the Westinghouse Electric Corporation, East Pittsburgh, Pa. Mr. Powel has first-hand knowledge of the expansion of Germany's electrical industry in pre-war years.

Speaking recently before the Pittsburgh Chamber of Commerce Mr. Powel said that his first task under the Allied Control Commission will be to make a survey to determine just how greatly this expansion overshot the nation's normal needs. Then a recommendation will be made to the commission as a basis for permissible future activity of the industry. He believed that somewhere between the two extremes of making Germany a completely agrarian nation, as advocated by some, and allowing it any and all industries on the basis that they are essential to European economy, as advocated by others, there must lie a middle road. This middle road would permit the Germans a satisfactory balance between agriculture and industry and give them a decent standard of living without allowing them to establish a new war potential.

Mr. Powel reiterated his belief in the merits of a plan previously suggested by him jointly with the presidents of four other major engineering societies—civil, mining, mechanical, and chemical. (*EE, Nov '44, p 393*)

Stratosphere Planes for Television and Frequency-Modulation Broadcasting

Airplane operation in the stratosphere as a new system of nationwide television and frequency-modulation broadcasting was announced as a joint development of Westinghouse Electric Corporation, East Pittsburgh, Pa., and The Glenn L. Martin Company, Baltimore, Md., at a luncheon in the Waldorf-Astoria Hotel, New York, N. Y., August 9, 1945. The Federal Communications Commission has been informed of the plan which specifies a low-powered ground transmitter to send television and frequency broadcasts to a specially designed high-altitude plane circling slowly overhead. The plane would be equipped with receivers and transmitters for rebroadcasting these programs back to the earth. As now conceived a chain of planes similar to the *B*-29, each cruising over a fixed area and spanning the continent, would transmit simultaneously five frequency-modulation programs and four television shows to listeners on the ground 30,000 feet below. It was asserted that this relay system would enable 14 airplanes to cover 78 per cent of the country's population and would eliminate the need for many hundreds of ground stations.

C. E. Nobles, a young radar engineer from Texas, affiliated with Westinghouse Corporation, is credited with being the originator of the Stratovision system. He explained the radio features of the new system at the luncheon. In operation a program from a frequency-modulation or television studio would be beamed upward from a ground transmitter to the plane circling overhead. The plane would relay the signal back to ground over a 422-mile area and at the same time relay the program to the plane circling in the next area. Mr. Nobles said that an advantage of the stratosphere station was that the power needed to impress a satisfactory signal on a receiver decreased with an increase in the transmitter's height. His estimate of cost for the first experimental plane was $500,000. On the matter of cost, Walter Evans, vice-president of the Westinghouse corporation, in charge of all radio activities, added that providing comparable service by ground installation would require approximately 100 costly relay towers and hundreds of transmitters; or a coaxial cable network estimated to cost $100,000,000.

W. K. Ebel, vice-president in charge of engineering for the Martin company, went into detail on weather conditions, and said that at a six-mile altitude storms except thunderheads are below. He stated that if the country were covered with aircraft operating at all times at 30,000 feet meteorological data would be available so that we would be able to forecast weather conditions even more accurately than at present, and we could concentrate aircraft as they are needed near storm areas. Claiming that one of the unusual features of the Stratovision system was the type of plane design—a huge heavy-load plane to fly only fast enough to remain safely aloft at very high altitudes, he said that "for once we are not trying to go anywhere in a hurry, but instead want to go nowhere slowly."

Figure 1. All-metal low-wing monoplane powered with two 1,450-horsepower engines

Figure 2. Plane-to-plane connections form a nationwide network

INDUSTRY • • • • •

Announce Stand on Federal Power Projects. One hundred and sixty-seven of the nation's electric light and power companies, representing a large part of the business-managed electric industry, in a joint statement on July 18, 1945, made known their position on proposed river developments by the United States Government. These developments, providing for the creation of the Missouri Valley Authority and other projects similar to Tennessee Valley Authority, as well as the completion of several already in operation, entail an estimated initial expenditure in excess of $3,850,000,000. Among the points made is one—Government may properly regulate business, but should not operate business.

Seminar at Stevens an Aid to Industry and Management

The series of seminar meetings started in May, 1945 for industrial executives by the War Industries Training School of Stevens Institute of Technology, Hoboken, N. J., has resulted in an exchange of ideas which has affected major problems in industrial management and planning, it was revealed by Robert H. Baker, director of the school, at the seventh and final session of the series on July 10. Twelve men prominent in industry, among them plant managers, general managers, and

industrial relations directors, attended the course which became known as the "Executives Club." Members of the class said that the informal discussions under the direction of a trained industrial psychologist had been invaluable as an aid to solving many of the problems that management currently faces.

The War Industries Training School was started in January 1941, under the engineering, science, management war training program of the United States Office of Education. Since that time it has had more than 4,800 course enrollments.

For Extensive Use of High Frequency. A new building is now under construction at the Cambridge, Ohio, plastics-division plant of the Continental Can Company, and new types of automatic compression- and injection-molding equipment, making extensive use of high frequency, will be installed. This division was recently awarded the Army-Navy "E."

PATENTS

To Protect Patents. Under date of July 31, 1945, the New York Times states that United States State Department officials are seeking the adoption of some form of international agreement which would recognize American patent rights by Russia on a royalty basis. This would serve as a protection for patents of the United States often involved in development contract deals with Russian Government agencies in the system inaugurated in 1931.

Erratum. In an item on standards for drafting practices (*EE, May '45, p 202*) it was stated that the War Department had outlined the scope of the work to include civil, mechanical, electrical, aeronautical, and marine engineering. . . . The work is a joint venture of the War Department and the Navy Department and is conducted under the direction of the Joint Army-Navy Committee on Specifications.

OTHER SOCIETIES

Committee Becomes Society. The American-Soviet Science Society is the new name of the Science Committee, National Council of American-Soviet Friendship, Inc., New York, N. Y. All members of the latter have been invited to membership in the society. It was recommended that scientists and technologists be eligible for membership in the new society. Under the auspices of this society 300 scientists attended a reception, August 21, at Columbia University, New York, N. Y., to honor Doctor Irving Langmuir, General Electric Company, Schenectady, N. Y., and five other members of the American delegation of 16 that attended the recent scientific congress in Moscow.

Technical Council Formed in Kansas City

Seventeen professional and technical societies of the Kansas City, Mo., area joined forces in establishing the Technical Societies Council for unified action in matters pertaining to the development of scientific endeavors. Some of the principal objectives include support for the establishment of better technical and scientific libraries in this region; encouragement for the initiation of educational courses of a technical and scientific nature in the schools of this area and coordination of the vocational-guidance activities of the constituent organizations; cooperation with civic, educational and government agencies in matters requiring professional assistance.

At the organization dinner-meeting held in Kansas City on July 9, 1945, Doctor W. M. Hoehn, member of the American Chemical Society and laboratory director of George A. Breon and Company was elected chairman. C. M. Lytle (M '42) assistant superintendent and supervisor, engineer and estimating, overhead system department, Kansas City Power and Light Company, was elected to the office of vice-chairman and Charles Briggs, member of the American Society of Mechanical Engineers, with the Burns and McDonnell Engineering Company to that of secretary-treasurer.

Headquarters of the newly formed Council will be in the offices of the Midwest Research Institute, Kansas City. Sarah C Lechtman, a member of the Institute's staff will be manager of publications and will issue a monthly publication devoted exclusively to the interests of the new Technical Council.

New Society Formed. The Society of Industrial Designers has been formed with temporary offices at 55 West 42d Street, New York, N. Y. The society will assume the tasks and responsibilities of a professional association. A code of professional practice is in preparation. Information, advice and assistance will be available to people and institutions engaged in teaching industrial design or engaged in public education in this field. According to the announcement every industrial designer in good standing in the United States will be eligible for membership in this society.

New Utilities Association. Formation of an industry-wide association of electric light and power companies with headquarters in Washington, D. C., was recently announced.

Among the aims of the association are the development of co-operation between governmental departments and agencies dealing with them and with the supply of electric power, and the presentation of facts concerning public benefits resulting from the operation of tax-paying electric utility companies as distinguished from Government ownership and operation. The organization, not yet permanently named, plans to conduct a broad program to demonstrate the contribution of the industry toward a balanced national economy.

HONORS

Accomplishments in Field of Aeronautics Cited

Doctor W. F. Durand, chairman of the division of engineering and industry of the National Research Council, Washington, has won the American Society of Mechanical Engineers Medal, the society's highest honor, for his work in aerodynamic science.

The Holley Medal of the society will go to Doctor S. A. Moss, General Electric Company engineer, West Lynn, Mass., for his many contributions to the development of centrifugal compressors, particularly to the application of turbo-superchargers to internal combustion engines in aeronautics.

The Worcester Reed Warner Medal will be awarded to Doctor J. M. Juran, assistant to the administrator of the Foreign Economics Administration, Washington, D. C., for his contribution to the problem of quality control in mass production, and for various other writings.

W. J. King, research engineer with the fuels division of Battelle Memorial Institute, Columbus, Ohio, is the winner of the Melville Prize Medal for his paper, "The Unwritten Laws of Engineering."

B. E. Del Mar, supercharging engineer with the Douglas Aircraft Company, Santa Monica, Calif., will receive the Junior Award for his paper, "Presentation of Centrifugal Compressor Performance in Terms of Nondimensional Relationships."

Honors and awards will be made at the society's meeting in New York, N. Y., in November 1945.

Wins Annual Report Contest. The Puget Sound Power and Light Company, Seattle, Wash., has won the 1944 award for the best annual report. The company won the prize in 1943 also. The purpose of the award, which is a bronze plaque, is to encourage the clarification of annual reports for the average reader. The winning report consisted of a 50-page bound booklet with a two-color cover, and a text replete with photographs.

Radios as Prizes for "GI's." Fifty postwar Bendix radio-phonograph combinations are being awarded as prizes in a war bond letter-writing contest for "GI's" in the European theater, Leonard C. Truesdell, general sales manager of radio and television, Bendix Radio division, recently announced. Certificates for postwar delivery of the combinations through distributor and dealer channels have been turned over to *Stars and Stripes*, official Army over eas newspaper, for awarding to those writing prize-winning letters on the subject, "My Savings and Postwar Plans." The contest is open to military personnel in Europe who have taken out a new war-bond allotment or have purchased a bond since May 1, 1945. The thousands of letters already received indicate that servicemen have thought about their postwar future.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Determination of the Individual Resistances of a Delta Mesh by Measurements Taken at the Junctions

To the Editor:

Testing and analysis of a-c equipment and machinery often require the resistance of the individual delta-connected windings. In some cases it is either impossible or inconvenient to isolate the windings for direct measurement. This paper offers a method by which the individual resistances may be calculated from resistance measurements taken between the junctions of the windings.

The resistance between the three combinations of pairs of terminals or junctions of three delta-connected windings may be measured by means of a Kelvin bridge or a Wheatstone bridge depending upon the magnitude of the winding resistances. The resistances thus measured will be the resistance of one winding in parallel with the other two windings in series. From these three measurements, three independent equations may be set up involving three unknown quantities.

Let

R_a = the resistance of winding *a*
R_b = the resistance of winding *b*
R_c = the resistance of winding *c*
R_{AB} = the measured resistance between terminals *A* and *B*
R_{BC} = the measured resistance between terminals *B* and *C*
R_{CA} = the measured resistance between terminals *C* and *A*

Then, by parallel circuits

$$R_{AB}=\frac{R_c(R_a+R_b)}{R_c+(R_a+R_b)} \tag{1}$$

$$R_{BC}=\frac{R_a(R_b+R_c)}{R_a+(R_b+R_c)} \tag{2}$$

$$R_{CA}=\frac{R_b(R_c+R_a)}{R_b+(R_c+R_a)} \tag{3}$$

These three independent equations may be solved for R_a, R_b, and R_c in terms of R_{AB}, R_{BC}, and R_{CA}. An inspection of these equations will show them to be nonlinear and their mathematical solution necessarily will be somewhat involved. This tedious mathematical solution can be avoided by making use of the delta-wye and the wye-delta transformations.

The delta mesh, $R_aR_bR_c$ can be replaced by the equivalent wye mesh, $R_a'R_b'R_c'$. Then

$$R_{AB}=R_a'+R_b' \tag{4}$$

$$R_{BC}=R_b'+R_c' \tag{5}$$

$$R_{CA}=R_c'+R_a' \tag{6}$$

If one solves equations 4, 5, and 6 for R_a', R_b', and R_c',

$$R_a'=\frac{R_{AB}-R_{BC}+R_{CA}}{2} \tag{7}$$

$$R_b'=\frac{R_{BC}-R_{CA}+R_{AB}}{2} \tag{8}$$

$$R_c'=\frac{R_{CA}-R_{AB}+R_{BC}}{2} \tag{9}$$

Transforming from the wye mesh to the equivalent delta mesh gives

$$R_a=\frac{R_a'R_b'+R_a'R_c'+R_b'R_c'}{R_a'} \tag{10}$$

$$R_b=\frac{R_a'R_b'+R_a'R_c'+R_b'R_c'}{R_b'} \tag{11}$$

$$R_c=\frac{R_a'R_b'+R_a'R_c'+R_b'R_c'}{R_c'} \tag{12}$$

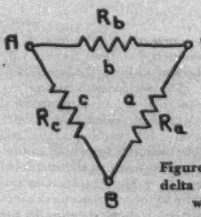


Figure 1. Three delta - connected windings

Substituting the values of R_a', R_b', and R_c' from equations 7, 8, and 9 in equations 10, 11, and 12 gives

$$R_c=\frac{\left(\frac{R_{AB}-R_{BC}+R_{CA}}{2}\right)\left(\frac{R_{BC}-R_{CA}+R_{AB}}{2}\right)+\left(\frac{R_{AB}-R_{BC}+R_{CA}}{2}\right)\left(\frac{R_{CA}-R_{AB}+R_{BC}}{2}\right)+\left(\frac{R_{BC}-R_{CA}+R_{AB}}{2}\right)\left(\frac{R_{CA}-R_{AB}+R_{BC}}{2}\right)}{\left(\frac{R_{AB}-R_{BC}+R_{CA}}{2}\right)}$$

$$=\frac{-R_{AB}^2-R_{BC}^2-R_{CA}^2+2R_{AB}R_{BC}+2R_{AB}R_{CA}+2R_{BC}R_{CA}}{2R_{AB}-2R_{BC}+2R_{CA}} \tag{13}$$

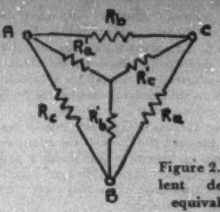


Figure 2. Equivalent delta and equivalent wye

Similarly

$$R_b=\frac{-R_{AB}^2-R_{BC}^2-R_{CA}^2+2R_{AB}R_{BC}+2R_{AB}R_{CA}+2R_{BC}R_{CA}}{2R_{BC}-2R_{CA}+2R_{AB}} \tag{14}$$

$$R_a=\frac{-R_{AB}^2-R_{BC}^2-R_{CA}^2+2R_{AB}R_{BC}+2R_{AB}R_{CA}+2R_{BC}R_{CA}}{2R_{CA}-2R_{AB}+2R_{BC}} \tag{15}$$

It will be noted that the numerators of equations 13, 14, and 15 are the same thereby reducing the arithmetical calculations after the measured values have been substituted.

LEE J. PURNELL (A '41)

(Associate professor and head of the electrical-engineering department, Howard University, Washington, D.C.)

The Engineering Degree

To the Editor:

The letter by C. W. Comstock in the June 1945 issue of *Electrical Engineering* expressed opinions on the value of college degrees which coincide with those developed by 38 years in a large, highly technical organization. During ten years of this period I was associated with a large plant school when we were changing from simple manual to very complicated mechanical operations. We had unusual opportunities for research, experiment and practical application in all phases of vocational aptitude testing and training. We found it possible to determine, even on 15-year old boys without previous experience or knowledge, whether individuals possessed inherent or potential faculties that fitted them for complicated electrical work. When this system was thoroughly established and had proved to be more than 90 per cent accurate, we discovered that approximately four out of five electrical engineering graduates were not natural born electrical experts. These men failed on simple tests easily mastered by 15-year old potential electricians.

Therefore, as a substitute for college degrees, we might have a system of scientific vocational aptitude testing to be based not on memory, but on a student's ability to demonstrate his powers of reasoning and practical application. An experience in Signal Corps training offers some illumination on this subject. One day a laboratory instructor bragged that his class of 20 signal men were able, after 16 weeks of training, to wire and clear trouble on a one-tube radio circuit. These men had been selected for radio training on the basis of Army classification tests. It was suggested that the instructor try an experiment in vocational psychology by drawing the one-tube circuit upside down on

the blackboard and asking just one question. "What case of trouble do you find on this circuit?" While difficult to believe, 19 out of these 20 men were very certain they found a wiring error in the circuit simply because they could not read it drawn upside down. In other words, only one man in 20 could reason about the circuit and this is a characteristic failure noted in too many electrical engineering graduates.

From an employer's point of view, a certificate based on accurate, practical application tests and guaranteeing potential or actual job proficiencies, would be much more satisfactory than the present academic degrees. Would be pleased to co-operate with anyone interested in this important subject.

FREEMAN HURD (M '43)

(Director, American Education Foundation, Inc., Chicago, Ill.)

Bactericidal Lamps

To the Editor:

Because of current activity by lighting-fixture manufacturers in preparing for the ultraviolet-radiation market, it would be proper for our engineers to exercise leadership in the dissemination of information to the public regarding the potential dangers to living tissue, in the use of bactericidal lamps emitting 2537 angstroms wavelength energy.

It is quite understandable that electric-maintenance men may clean or relamp such fixtures without killing the circuit. The writer's own experience has been that five seconds radiation at two feet will give sore eyes within eight hours. We do not want an energy source of such undeveloped potentialities as the bactericidal lamp, to gain ill repute because of unguided use by the public. It therefore behooves the technical man to safeguard the public perhaps through the organization of a clearing house for information by a recognized society, for the purpose of assisting the manufacturer and the retailer in the proper presentation of this energy source to the public.

E. J. CONTIER (A '45)

Plant electrician, Monroe Calculating Machine Company, Orange, N. J.

NEW BOOKS

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

An Introduction to Electronics. By Ralph G. Hudson. The Macmillan Company, New York, N. Y., 1945. 97 pages, illustrated, $5\frac{1}{2}$ by $8\frac{1}{4}$ inches, $3.

Explains the science of electronics by acquainting the layman with some of the outstanding new concepts of the physical world together with the implications of their probable effect upon his manner of living. This exposition emphasizes how electrons perform and why. Aside from the astronomical figures and exceedingly small numbers that pervade the literature of electronics, the book contains practically no mathematics and presupposes no previous study of physics or chemistry. It describes the major uses of electronic tubes and phototubes, the construction of electronic devices and their working principles and paints a vivid picture of "radar"—what it has accomplished in these war years and what its unlimited possibilities portend for tomorrow.

The Simple Calculation of Electrical Transients. By G. W. Carter. Cambridge: At the University Press. The Macmillan Company, New York, N. Y., 1945. 120 pages, $5\frac{1}{4}$ by $7\frac{3}{4}$ inches, $1.75.

An elementary treatment of transient problems in linear electrical circuits, by Heaviside's operational method. Based upon a course of lectures given to engineers of the British Thomson-Houston Company, Limited, the book has been written with a bias toward the physical or engineering side. The ground covered is limited to the behavior of linear circuits with lumped elements. As little previous knowledge as possible has been assumed, but some knowledge which must be taken for granted has been summarized in the last four Appendices. The final chapter consists of worked-out examples, which illustrate the book's principal themes.

Introduction to Practical Radio. By D. J. Tucker. The Macmillan Company, New York, N. Y., 1945. 322 pages, illustrated, $5\frac{3}{4}$ by $8\frac{1}{4}$ inches, cloth, $3.

Text is confined to initial principles and basic fundamentals of radio. Necessary mathematics is included, and numerous specific examples of the practical application of principles to actual radio construction and operation are given. Provides a reference work for practicing radio engineers and technicians as well as a complete manual for beginners. The chapters on elementary electricity, Ohm's Law, resistance circuits, direct-current power and magnetism might serve as a valuable refresher course for more advanced students. Such valuable additions as a list of symbols and their meaning, a mathematical and an electrical glossary and an appendix of logarithmic and trigonometric tables are included.

Transmission Lines Antennas and Wave Guides. By R. W. P. King, H. R. Mimno, and A. H. Wing. McGraw-Hill Book Company, New York 18, N. Y., 1945, 347 pages, $5\frac{1}{2}$ by $8\frac{1}{2}$ inches, cloth, $3.50.

This book is an outgrowth of a special wartime pre-radar training course given in the Graduate School of Engineering, Harvard University, Cambridge, Mass. Transmission lines are presented exclusively from the high-frequency point of view; antennas from the electromagnetic theory; and wave guides are presented from the point of view of generalized transmission circuits. The section on wave propagation is brief and is intended primarily for students with a general knowledge of physics who have had no previous opportunity to study the basic principles of radio transmission.

Engineering Preview, an introduction to engineering including the necessary review of science and mathematics. By L. E. Grinter and others. The Macmillan Company, New York, 1945. 581 pages, illustrated, $9\frac{1}{2}$ by 6 inches, cloth, $4.50 (ESL.)

Designed for high-school seniors or college freshmen, this textbook treats the background science of engineering—mathematics, chemistry, and physics—technical drawing and some of the basic engineering applications of physics. The object is to present in an organized way the background material for later study of any specialized field of engineering and thus enable the reader to determine whether engineering is his field.

(The) New Plastics. By H. R. Simonds and M. H. Bigelow, assisted by J. V. Sherman. D. Van Nostrand Company, New York, N. Y., 1945. 320 pages. $8\frac{3}{4}$ by $5\frac{1}{2}$ inches, cloth, $4.50. (ESL.)

This book presents the available information on all important plastic materials developed since 1940. Separate chapters are devoted to the new fibers, new adhesives, new laminating materials, new applications of wood and paper, new forms and coatings. New and improved processes and applications for established plastics are covered, and the trend of the plastics industry is demonstrated as indicated by summarized statistical and technical information.

Dynamic Meteorology. By J. Holmboe, G. E. Forsythe and W. Gustin. John Wiley and Sons, New York, N. Y., Chapman and Hall, London, England, 1945. 378 pages, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $4.50. (ESL.)

Intended as a basic introduction to theoretical meteorology, this text starts from the fundamental principles of physics, and develops the tools of thermodynamics and hydrodynamics needed for the understanding of atmospheric motion. Only material which is considered indispensable for the practical meteorologist and weather forecaster has been included. A general knowledge of physics and calculus is assumed.

Treatise on the Theory of Bessel Functions, 2d ed. By G. N. Watson. The Macmillan Company, New York, N. Y., The University Press, Cambridge, England, 1945, 804 pages, $10\frac{1}{4}$ by $7\frac{1}{4}$ inches, cloth, $15.00. (ESL.)

The mathematical aspects of Bessel functions are discussed with two main objects: the development of applications of the fundamental theory of functions of complex variables, and the compilation of a collection of results which would be of value to the increasing number of mathematicians and physicists who encounter Bessel functions in their investigations. An extensive bibliography is included.

Industrial Organization and Management. By L. L. Bethel, F. S. Atwater, G. H. E. Smith and H. A. Stackman, Jr. McGraw-Hill Book Company, New York, N. Y., and

London, England, 1945. 798 pages, 9 by 5¾ inches, cloth, $4.50. (ESL.)

Management as a field of specialization within itself, rather than as an adjunct to the study of engineering or business, is the subject of this basic text. It prepares the student for advanced work in methods, cost, industrial relations, budgeting, production control, marketing, and office management.

Chemistry of Coal Utilization. Prepared by Committee on Chemical Utilization of Coal, Division of Chemistry and Chemical Technology, National Research Council. John Wiley and Sons, New York, N. Y., Chapman and Hall, London, England, 1945. 1868 pages, 9 by 6 inches, cloth, $20.00 (2 Vols.). (ESL.)

Prepared by a staff of 35 contributors, this two-volume treatise constitutes a comprehensive and critical review of the voluminous but scattered literature on the scientific and practical aspects of coal utilization.

Air News Yearbook, Vol. 2. Duell, Sloan and Pearce, New York, N. Y., 1944. 296 pages, 9 by 12 inches, cloth, $4.75. (ESL.)

Extensive chapters on the development and operation of the air forces of the principal world powers are illustrated by some 400 photographs. Individual descriptive material is provided for all planes shown, and plane types are arranged according to the countries of their origin.

Fundamentals of Thermodynamics. By A. S. Adams and G. D. Hilding. Harper and Brothers, New York and London, 1945. 289 pages, 9½ by 6 inches, cloth, $3.75. (ESL.)

The object of the authors is to give the beginning student an understanding of the fundamentals of thermodynamics adequate for further related study in mechanical engineering, physics and chemistry.

Elementary Statistics. By H. Levy and E. E. Preidel. Ronald Press Company, New York, 1945. 184 pages, 7¾ by 5 inches, cloth, $2.25. (ESL.)

Presents the principles of statistics briefly and simply, without requiring more mathematics than elementary algebra. It is based on courses given to students of mathematics, physics, and engineering at the Imperial College of Science, London, England.

Coming Age of Rocket Power. By G. E. Pendray. Harper and Brothers, New York and London, 1945. 244 pages, illustrated, 8¼ by 5¼ inches, cloth, $3.50. (ESL.)

The evolution of the rocket principle, from its discovery ages ago to such modern developments as the bazooka and the rocket plane.

Report of the Urban Planning Conferences at Evergreen House, 1943. Johns Hopkins Press, Baltimore, Md., 1944. 245 pages, illustrated, 9½ by 6 inches, $2.75. (ESL.)

Presents results of a series of six conferences held under the auspices of Johns Hopkins University and participated in by many experts. The subjects discussed were the basic directives in urban planning, transportation; housing; health; recreation, and welfare.

PAMPHLETS • • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

The Distribution of Thunderstorms and the Frequency of Lightning Flashes. National Research Council of Canada, Ottawa, Ont., Canada. A review by R. Ruedy, Research Plans and Publications Section. Second edition, revised and enlarged. April 1945, 70 pages, $1.

The Government's Wartime Research and Development, 1940–1944. Part 11. Findings and Recommendations. July 1945. Report from the Subcommittee on War Mobilization to the Senate Committee on Military Affairs. By H. M. Kilgore, 74 pages.

American Standards (Price List of American Standards, American Safety Standards, American War Standards, and Alphabetical Index to American Standards). American Standards Association, New York 17, N. Y. 24 pages.

Wartime Technological Developments. Subcommittee on War Mobilization of the Committee on Military Affairs United States Senate. United States Bureau of Labor Statistics. 418 pages, 50 cents.

Ohio's Mineral Resources. III Salt (In Two Parts). By S. P. Hildreth, and W. R. Harris and E. J. Corell. Engineering Experiment Station, Ohio State University, Columbus, Ohio, July 1945. 19 pages.

Science of Measurement. Book 1–Book 8. A study course in tool inspection and the instruments that make for precision. Continental Machines, Inc., Minneapolis 4, Minn.

Test Specifications Automatic Electric Storage Water Heaters. Report of a joint committee of the Edison Electric Institute and National Electrical Manufacturers Association, New York, N. Y., 10 pages.

A Survey of Technical Institutes by Leo F. Smith (*Technical Education News*), McGraw-Hill Book Company, New York, N.Y., 4 pages.

Facts in Figures About Atlanta. Industrial Bureau, Atlanta Chamber of Commerce Atlanta, Ga., 40 pages.

Rotameter Nomograph for Steam. Fischer and Porter Company, Hatboro, Pa. (Chart on rotameter size for steam measurement).

Radar. (Official history of the new science with technical descriptions and glossary of Radar terms.) June 1945. British Information Services, New York, N. Y. 30 pages.

A New Era in Flow Rate Measurement (third revised edition). Fischer and Porter Company, Hatboro, Pa., 32 pages.

The Decimal Point and the Slide Rule (including some time-saving short-cuts for electrical engineers and technicians). By W. P. Miller, 5 pages.

The National Association of Public Relations Counsel, Inc. Its origin; its purpose; its work. International Building, Rockefeller Center, New York 20, N. Y.

Aircraft Accessories For 400 Cycle Motor Operation. By R. G. Holt. Pesco Products Company, Cleveland 6, Ohio, 10 pages.

Books, Publications and Patents, 1929–1944. Battelle Memorial Institute, Columbus, Ohio, 72 pages.

Contractors Guide. War and Navy Departments. (An aid in the settlement of terminated war contracts), 60 pages, free.

Directory of Products and Engineering Literature. Allis-Chalmers Manufacturing Company, Milwaukee, Wis., 32 pages.

First Time in History! The Duplex Speaker. Altec Lansing Corporation, Hollywood 28, Calif., 12 pages.

How to Do Business with RFC. Reconstruction Finance Corporation, Washington, D. C. 32 pages.

Industrial Electronic Tube Manual. General Electric Company, Schenectady, N. Y., 412 pages, $2.

Instrument Manufacturing and Service Facilities. Nilsson Electrical Laboratory, Inc., New York 13, N. Y., 20 pages.

Introduction to Electronics. By Walther Richter. Allis-Chalmers Manufacturing Company, Milwaukee, Wis., 19 pages.

NEMA Standards for Electric Water Heaters. Publication No. 45-104. New York, N. Y., eight pages, 25 cents.

New Designations of Screens for Cathode-Ray Photography. Allen B. Du Mont Laboratories, Inc., Passaic, N. J.

OPA Reports to Congress. By Chester Bowles to the Banking and Currency Committees. March 1945, 104 pages.

Rotating-Blade Air-Break Switch. (Type TW), Pacific Electric Manufacturing Corporation, San Francisco 24, Calif., 16 pages.

Standards Review (Period Review of the British Standards Institution). The London Press Exchange Ltd., 1945, No. 1, 2 shillings.

The Ignitron Tube and How It Is Used. General Electric Company, Schenectady, N. Y., 23 pages.

We Had to Have Rubber. The Rubber Manufacturers Association. New York 22, N. Y., 64 pages.

9-Inch South Bend Precision Lathes. South Bend (Ind.) Lathe Works, 35 pages.

Dillon Dynamometer. W. C. Dillon and Company, Chicago 44, Ill., 19 pages.

Television As a Career. General Electric Company, Schenectady, N. Y., 4 pages.

Theory of the Rotameter. Fischer and Porter Company, Hatboro, Pa., 23 pages.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Statistics as an Aid to Engineering Judgment in the Manufacture of Lightning-Arrester Blocks

CASPER GOFFMAN
NONMEMBER AIEE

IN THIS PAPER we show how modern statistical methods may be used as an aid to engineering judgment in determining the causes of variability in a complex manufacturing process.

Assistant Secretary of War for Air Lovett has said that "a statistician is a man who can lead you directly from a preconceived idea to a foregone conclusion." If properly interpreted, this statement contains an element of truth. But it is not the kind of statement which should be made under oath. For while it is the truth and nothing but the truth, it certainly is not the whole truth. The whole truth might be phrased in similar language as follows: "Among a given class of preconceived ideas, the statistician can tell, with a definite degree of certainty, which subclass constitutes foregone conclusions."

In our particular example on lightning-arrester blocks, the set of preconceived ideas are the variables in the process of manufacturing blocks which were thought to affect the electrical characteristics of blocks. The foregone conclusions are those among these variables which actually do affect significantly the electrical characteristics of the blocks. The term "significantly" is used here in an engineering sense—not a statistical sense.

Production Procedure

A brief description will be given of the production and testing of blocks.

The blocks consist of silicon carbide and a binder. The electrical characteristics of the silicon carbide are the determining factor of fitness for use.

The silicon carbide and binder are mixed in suitable proportions. After proper mixing, the material is screened and stored and is ready for molding into blocks.

The amount of material to be molded per block is weighed, by machine, directly into the mold with the bottom punch in place. The top punch then is inserted and the block pressed. The blocks then are subjected to a 24-hour baking cycle.

The ends of the blocks are sprayed with copper, and the lateral surfaces are coated with an insulating compound.

Figure 1 shows a lightning-arrester block cut through the middle.

Testing Procedure

The blocks are subjected to a life test and a volt-ampere characteristic test. We are here interested in the latter only. The functioning of a lightning-arrester block depends upon the fact that its resistance does not vary linearly. It has high resistance for low currents and low resistance for high currents. Figure 2 shows the volt-ampere characteristics of a lightning-arrester block taken by a cathode-ray oscillograph. The block is subjected to a surge whose crest value is 1,500 amperes. The time of the surge is ten microseconds from zero current to maximum and 20 microseconds to half value. The volt-ampere characteristic is read on a cathode-ray oscillograph. The maximum voltage attained across the block is called the "maximum rise" of the block.

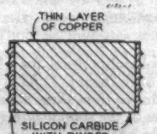


Figure 1. Lightning-arrester block

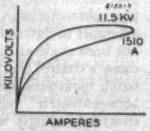


Figure 2. Volt-ampere characteristic curve of lightning-arrester block

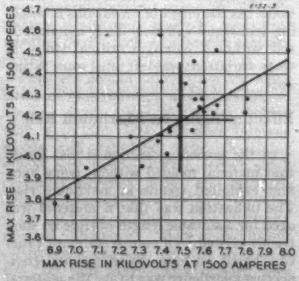


Figure 3. Correlation between maximum rise at 150 amperes and 1,500 amperes

Variables

Among the known factors which could cause electrical variations are such things as weight, length, and density of blocks; variations in the manufacturing techniques, and the character of the raw silicon carbide; and variations in the testing equipment.

Correlation Between Two Tests

As the voltages across the block at both high and low currents are important in the functioning of the blocks, it is of value to know the degree of correlation between these voltages.

Accordingly, for a set of 30 blocks, maximum rise was obtained for a 150-ampere surge and for a 1,500-ampere surge. The data were plotted on a scatter diagram as shown in Figure 3. The regression of Y on X is given by the equation $Y = 0.5X$. The calculation given in Table I shows that the regression is highly significant.

The 0.01 probability level for F with 1 and 28 degrees of freedom is about 8.0. Hence the regression is highly significant.

It may be of interest to note that the dependence of Y on X may be inferred from the fact that only two of the 30 points in Figure 3 fall in the second and fourth quadrants. The chance that this will happen for uncorrelated data is one in 2,000,000. For that reason, plus the fact that the variance from the regression line is small, the test for a 150-ampere surge was eliminated.

Effect of Molding Technique on Electrical Characteristics

To determine the effect of variations in molding technique on electrical characteristics of blocks, a batch of material was mixed and divided into four portions

Paper 45-132, recommended by the AIEE subcommittee on applications to statistical methods of the Standards committee for publication in AIEE TRANSACTIONS. Manuscript submitted April 30, 1945; made available for printing May 15, 1945.

CASPER GOFFMAN is staff assistant, quality-control department, Westinghouse Electric Corporation, East Pittsburgh, Pa.

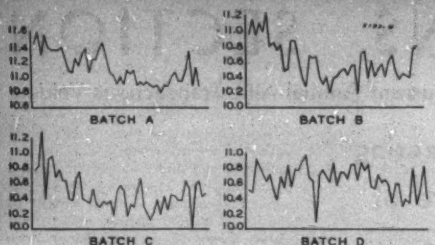
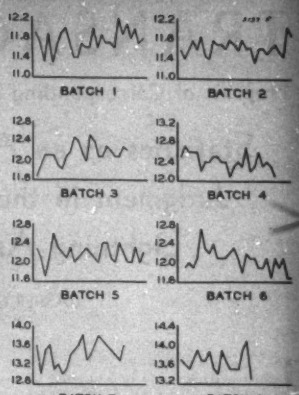


Figure 4 (left). Trends shown by data obtained in experiment on molding technique

	Batch A	Batch B	Batch C	Batch D
$ns^2 =$	2.0113	3.0102	3.3774	1.8208
$(n-1)s^2 =$	1.1691	2.3625	2.3576	3.1626
$s^2/\sigma^2 =$	0.585	0.787	0.693	1.738

Figure 5 (right). Effect of aging on stabilizing electrical characteristics of blocks



Batch 1	$ns^2 = 1.53$	$(n-1)s^2 = 1.69$	$s^2/\sigma^2 = 1.69$
Batch 2	$ns^2 = 0.75$	$(n-1)s^2 = 1.47$	$s^2/\sigma^2 = 1.96$
Batch 3	$ns^2 = 0.99$	$(n-1)s^2 = 1.10$	$s^2/\sigma^2 = 1.11$
Batch 4	$ns^2 = 0.65$	$(n-1)s^2 = 1.08$	$s^2/\sigma^2 = 1.67$
Batch 5	$ns^2 = 0.88$	$(n-1)s^2 = 1.52$	$s^2/\sigma^2 = 1.73$
Batch 6	$ns^2 = 1.38$	$(n-1)s^2 = 1.68$	$s^2/\sigma^2 = 1.22$
Batch 7	$ns^2 = 1.16$	$(n-1)s^2 = 1.56$	$s^2/\sigma^2 = 1.34$
Batch 8	$ns^2 = 0.77$	$(n-1)s^2 = 1.52$	$s^2/\sigma^2 = 1.98$

from each of which 50 blocks were molded under different conditions. These will be called batches A, B, C, and D.

Batch A was molded in the laboratory under controlled conditions. Batches B, C, and D were molded in the shop. For B the attempt was made to control the variables. For C no attempt at control was made, but the operator was under observation. Batch D was molded without letting the operator know that it was a special batch.

Incidentally, since batches A, B, and C were molded immediately after mixing, and batch D was molded several days later, this experiment shows the effect of aging on maximum rise. Thus a trend definitely exists for batches A, B, and C, although it is not so evident for batch D. See Figure 4. The statistic s^2/σ^2 has values of 0.585, 0.787, 0.693, and 1.738 for batches A, B, C, and D, respectively. The 0.01 and 0.05 probability values for this statistic for 50 observations are 1.40 and 1.58, respectively.

The following application of the χ^2 test was made to see whether significant differences exist between the variances of the afore-mentioned four batches.

$$\chi^2 \cong \frac{2.3026}{C}\,(n \log S'^2 - \Sigma n_i \log S_i'^2)$$

with $K-1$ degrees of freedom, where $S_i'^2$ is the estimated ith variance with n degrees of freedom and S'^2 is the estimated total variance with n degrees of freedom.

$$C = 1 + \frac{1}{3(k-1)} \sum \left(\frac{1}{n_i} - \frac{1}{n}\right)$$

In this case,

$$\chi^2 \cong \frac{2.3026}{1.01}\,(196 \log 0.0462 - 49 \log 0.00000349)$$
$$= 2.3\,(-261.73 + 267.40)$$
$$= 13.04$$

But the 0.01 probability level for χ^2 with three degrees of freedom is 11.34.

The conclusion drawn from these data is that the variables of the shop molding practice actually do affect the volt-ampere characteristics of blocks. Further attempts to determine these factors have not been made at this time, primarily because a control chart showed that within-batch variations were small compared to between-batch variations. Maximum effort accordingly was devoted to eliminating causes of between-batch variations. As the effect of variations in molding technique will most likely manifest itself within a batch, a critical study of these variations was left until some future date.

Table I

	Sum of Squares	Degrees of Freedom
Total	1.0099	29
Regression	0.6881	1
Error	0.3218	28

$$F = 0.6881 \div \frac{0.3218}{28} = 60$$

Table II

Before Aging	After Aging
0.585	1.69
0.787	1.96
0.693	1.11
	1.67
	1.73
	1.22
	1.34
	1.98
$\bar{X} = 0.69$	$\bar{Y} = 1.59$

Effect of Aging on Maximum Rise

In the preceding section it was found that material molded without being aged first exhibited trends in maximum rise. The indication was that if material was aged for a suitable length of time no such trends existed. Of course standard practice based on long experience and engineering knowledge was to age the material before using. However, statistical analysis brings a definiteness into the picture which otherwise seems to be lacking and sometimes refutes accepted practice. For this reason, the data shown in Figure 5 were obtained for eight batches aged for what was considered to be a sufficiently long period of time. The data are for every eighth block in order of production. The values of s^2/σ^2 for the eight batches were respectively 1.69, 1.96, 1.11, 1.67, 1.73, 1.22, 1.34, and 1.98. That trends exist even after aging is evident from the fact that all eight values obtained are less than two, which is the expected value of this statistic if there are no trends. However, the trend obtained after aging is significantly less than that obtained before aging as shown by the t test in Table II.

$$t = \frac{\bar{Y} - \bar{X}}{\sqrt{\left(\frac{1}{n_1} + \frac{1}{n_2}\right) \frac{\Sigma(\bar{X} - X)^2 + \Sigma(\bar{Y} - Y)^2}{n_1 + n_2 - 2}}}$$
$$= \frac{90}{\sqrt{(1/6 + 1/4)\,\frac{(0.02 + 0.7550)}{9}}}$$
$$= \frac{0.90}{0.198} = 4.54, \text{ 9 degrees of freedom}$$

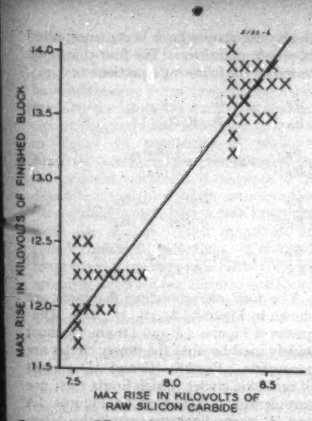


Figure 6. Effect of maximum rise of raw silicon carbide on maximum rise of finished blocks

The 0.01 probability level with nine degrees of freedom is 3.25. Hence the difference is significant.

Effect of Baking Temperature on Blocks

Sixteen blocks were taken from the same batch. Eight of the blocks selected at random were baked in an oven at the standard temperature. The other eight blocks were subjected to a baking cycle whose maximum temperature was 75 degrees centigrade lower. The data are shown in Table III. A value of $t =$ 1.89 was obtained. This falls between the 0.05 and 0.10 probability level of the t distribution. A retest was made with 16 more blocks. A value of $t = 3.63$ was obtained. This value is higher than the 0.01 probability level, which shows that oven temperature should not be allowed to deviate by as much as 75 degrees centigrade.

Table III

Hot Oven	Cool Oven
First Test	
12.94	13.92
13.17	13.67
13.14	12.64
12.64	12.83
12.81	13.36
13.42	13.57
12.90	13.14
12.67	13.22
$\bar{X} = 12.96$	$\bar{Y} = 13.29$

$$t = \frac{13.29 - 12.96}{\sqrt{\frac{1}{14}(1.6809)}} = \frac{0.33}{17} = 1.94$$

Retest	
12.53	12.53
12.37	13.22
12.48	13.01
12.77	12.97
12.53	12.96
12.81	13.03
12.76	12.82
12.52	13.43
$\bar{X} = 13.60$	$\bar{Y} = 13.00$

$$t = \frac{13.00 - 12.60}{\sqrt{\frac{1}{14}(0.6697)}} = \frac{0.40}{0.11} = 3.63$$

To determine whether or not significant differences in electrical characteristics exist between blocks baked in various positions in the oven, 32 blocks were randomized and placed in groups of four in eight positions in the oven. The data are shown in Table IV. An analysis of variance performed with these data yields a value of $F = 0.696$ with seven degrees of freedom for the between-position variance and 16 degrees of freedom for the error term (within-position variance). This test indicates strongly that significant differences do not exist between positions in oven as far as electrical characteristics are concerned.

Table IV

Position 1	2	3	4	5	6	7	8
12.3	12.6	12.3	12.3	12.4	12.4	12.3	12.8
12.1	12.3	12.0	12.2	12.4	12.2	12.0	12.4
12.2	12.2	12.1	12.1	12.2	12.2	12.2	12.3
11.7	12.1	12.2	12.2	12.0	12.0	12.3	12.1
Average 12.075	12.3	12.15	12.2	12.25	12.2	12.2	12.375

$\bar{X} = 12.20$

Total sum of squares = 0.86 — 31 degrees of freedom
Between positions = 4(0.03625) = 0.145 — 7 degrees of freedom
Error = 0.715 — 24 degrees of freedom

$$F = \frac{0.145/7}{0.715/24} = 0.696$$

Effect of Clearance Between Mold and Punch on Electrical Characteristics of Blocks

There had been some indication in the shop that blocks molded with large clearance between mold and punch had different electrical characteristics from blocks molded with small clearance. Although there was no apparent reason for this difference, a test was made to determine whether or not such a difference actually exists.

Fourteen blocks taken from the same batch of material were molded as special blocks; every other block was molded with a certain large clearance between molds and punches. The remaining blocks were molded with a certain small clearance between molds and punches. The results are shown in Table V. A value of $t = 10.1$ was obtained. This shows significant difference. That a significant difference exists also may be seen from the fact that every block molded with large clearance had a higher maximum rise than every block molded with small clearance.

Characteristics of Raw Silicon Carbide

The electrical characteristics of raw silicon carbide are obtained by getting the volt-ampere curve for a sample of the raw material. It would be of value to verify the degree of correlation between the maximum rise of raw material and finished product although theoretically the two should be proportional. However, at the time the test was run only two varieties were available. One had a maximum rise of 7.5 kv, the other 8.2 kv. The data are plotted in Figure 6 and show that the maximum rise of finished blocks is roughly proportional to the maximum rise of raw silicon carbide. The test should be repeated with batches of silicon carbide whose electrical characteristics vary along the scale to determine the regression lines.

Table V

Large Clearance	Small Clearance
12.6	12.1
12.6	11.9
12.8	12.0
13.2	11.9
13.0	11.9
12.6	11.8
13.0	11.9
$\bar{X} = 12.825$	$\bar{Y} = 11.9375$

$$t = \frac{0.8875}{\sqrt{\frac{0.43(1/4)}{14}}} = 10.1$$

Conclusion

As applied to lightning-arrester blocks, statistics helped engineering judgment by verifying that some of the variables which had been thought to affect electrical characteristics actually did so. This led to emphasis of control of these factors at the expense of others which had been thought to affect maximum rise but were found, by statistical analysis, to have a less significant effect. As a consequence of this study a more uniform product is

New Transmission-Line Diagrams

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IN THE DESIGN and operation of transmission lines the following quantities are of primary importance: sending-end power, receiving-end power, sending-end voltage, receiving-end voltage, power angle between sending-end and receiving-end voltage. Numerous diagrams have been developed for the solution of transmission-line problems, graphically illustrating relations between some of the afore-mentioned quantities. Among these, the modified Evans and Sels charts, based on the general circuit constants *ABCD*, have found wide acceptance.[1,2,3] In these charts the determination of the power at one end with the power given at the other end requires a transfer of points from one chart to another. It is one of the purposes of this paper to supplement the modified Evans and Sels diagrams in such a manner that this transfer of points can be eliminated. This can be accomplished by relating power at one end to power at the other end directly, without intermediate quantities such as voltage ratio and power angle. The diagrams developed are essentially admittance-circle diagrams, relating admittance at one end to admittance at the other end.

It is a further purpose of this paper to develop corresponding circle diagrams for the impedances, directly relating the impedance at one end to the impedance at the other. These diagrams might be useful in conjunction with impedance-relaying problems where a transfer through voltage ratio and power angle is not essential.

The modified Evans and Sels charts apply to fixed circuit constants. For each new set of values *ABCD*, a new chart must be prepared. Numerous charts have been developed to eliminate this shortcoming, resulting in universal transmission-line charts. These charts permit the determination of the performance of any line with arbitrary constants. In many of these charts it is necessary, however, to execute certain constructions to arrive at solutions. It is a further purpose of this paper to develop a universal transmission-line chart based on general circuit constants from which all the desired values can be read directly.

The following equations and notations will be used:

$$E_S = AE_R + BI_R \tag{1}$$

$$I_S = CE_R + DI_R \tag{2}$$

$$AD - BC = 1$$

$$\frac{E_R}{E_S} = \frac{|E_R|}{|E_S|}\underline{/-\delta}$$

where bars enclosing a quantity indicate magnitude.

δ = angle that E_S leads E_R = power angle

Vector power usually is defined by its components P, Q. In order to simplify the following formulas a single symbol denoting vector power representing a complex quantity is introduced:

$$\dot{p} = P + jQ = \text{power vector}$$

$$\frac{\dot{p}_S}{|E_S|^2} = Y_S = G_S + jB_S = \text{sending-end (input) admittance}$$

$$\frac{\dot{p}_R}{|E_R|^2} = Y_R = G_R + jB_R = \text{receiving-end (load) admittance}$$

$$\frac{\dot{p}_S}{|E_R|^2} = Y_{RS}; \qquad \frac{\dot{p}_R}{|E_S|^2} = Y_{SR}$$

Circle Diagram for the Calculation of Power at One End From Power at the Other End

The modified Evans and Sels charts are essentially admittance diagrams. For practical purposes, however, they are labeled in terms of power divided by the square of voltages. As the use of admittances produces more compact equations, admittance quantities will be employed freely, the results later being interpreted in power quantities. The four charts are based on the following equations:

$$\frac{\dot{p}_S}{|E_S|^2} = Y_S = \frac{D}{B} - \frac{1}{B}\frac{|E_R|}{|E_S|}\underline{/-\delta} \tag{3}$$

$$\frac{\dot{p}_R}{|E_R|^2} = Y_R = -\frac{A}{B} + \frac{1}{B}\frac{|E_S|}{|E_R|}\underline{/\delta} \tag{4}$$

$$\frac{\dot{p}_S}{|E_R|^2} = Y_{RS} = \frac{D}{B}\frac{|E_S|^2}{|E_R|} - \frac{1}{B}\frac{|E_S|}{|E_R|}\underline{/-\delta} \tag{5}$$

$$\frac{\dot{p}_R}{|E_S|^2} = Y_{SR} = -\frac{A}{B}\frac{|E_R|^2}{|E_S|} + \frac{1}{B}\frac{|E_R|}{|E_S|}\underline{/\delta} \tag{6}$$

The four corresponding diagrams are shown in Figures 1A, 1B, 1C, 1D. Diagrams of Figures 1A and 1B are the most widely used because the power circles are concentric. Figures 1C and 1D consist of eccentric circles, which limits their use considerably. Referring to Figures 1A and 1B, these diagrams permit the determination of the power and voltage quantities at one end from the power and voltage quantities at the other end. For instance, if it is desired to determine $P_S + jQ_S$ for a given $P_R + jQ_R$ and a known receiving-end voltage E_R, $P_R/|E_R|^2$ and $Q_R/|E_R|^2$ are computed, locating a point in the receiver-end chart, Figure 1B. This point determines the value of $|E_S/E_R|$ and δ. The corresponding point with identical $|E_S/E_R|$ and δ next is located in the sending-end diagram, Figure 1A whereupon the values $P_S/|E_S|^2$ and $Q_S/|E_S|^2$ can be read, and P_S, Q_S, and E_S can be computed. The necessity of transfer of points is common to all these modified diagrams since, essentially, they relate an admittance to the voltage ratio and power angle. It can be eliminated only if sending-end admittance and receiving-end admittance are brought in direct relation, as follows:

$$\left.\begin{aligned} Y_S &= \frac{I_S}{E_S} = \frac{CE_R + DI_R}{AE_R + BI_R} = \frac{C + DY_R}{A + BY_R} \\ Y_S &= \frac{D}{B} - \frac{1}{B^2\left(Y_R + \dfrac{A}{B}\right)} \end{aligned}\right\} \tag{7}$$

or, in vector-power form:

$$\frac{\dot{p}_S}{|E_S|^2} = \frac{P_S + jQ_S}{|E_S|^2} = \frac{D}{B} - \frac{1}{B^2\left(\dfrac{P_R + jQ_R}{|E_R|^2} + \dfrac{A}{B}\right)} \tag{7a}$$

being made, and an appreciable reduction in the scrap loss during manufacturing has resulted.

Statistical methods now are being further applied to determine superior designs. The main tool being used for this purpose is the designed experiment.

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In equation 7, Y_S is represented as an analytic complex function of the independent variable Y_R. Analytic functions have interesting properties which are particularly useful in the analysis of electric-circuit diagrams and which are described in detail in mathematical texts.[4,5,6] Analytic functions map the plane of the independent variable into the plane of the dependent variable in such a manner that corresponding infinitely small configurations are similar. Such mappings are called conformal mappings. Conformal mapping retains the angle between corresponding intersecting lines, in particular, an orthogonal system of lines in one plane transforms into another orthogonal system in the other plane.

Y_S is called a linear fractional transformation of Y_R. Since the mappings produced by this function have been discussed in detail before,[4] it will be sufficient to indicate the steps leading to the final $Y_S=f(Y_R)$ diagram. Analyzing the expression $1/(Y_R+A/B)$, the Y_R plane with origin OY_R and axis G and B is drawn (Figure 2). Addition of A/B produces the Y_R+A/B plane with origin O. In this plane, lines B_1=constant and G_1=constant are drawn. It is well known that the expression $1/(Y_R+A/B)$ can be obtained by a process of complex inversion. Inversion transforms circles into circles. Specifically, the straight lines B_1=constant and G_1=constant are transformed into the circles B_1=constant and G_1=constant respectively, as shown. Additional lines G=constant and B=constant all intersect at O and produce an orthogonal system of circles. Centers of the G=constant circles are located on the real axis, centers of the B=constant circles on the imaginary axis. The diameter of the circles is the reciprocal of the shortest distance of the straight lines from the origin and readily can be computed as shown in Figure 2. The final expression of Y_S requires multiplication of $1/(Y_R+A/B)$ by $-1/B^2$ and addition of D/B, resulting in Figure 3, which lists in detail the steps necessary to arrive at the circles $G=P_R/|E_R|^2$=constant and $B=Q_R+|E_R|^2$=constant in the $P_S/|E_S|^2+jQ_S+|E_S|^2$ plane. If numerous circles representing varying $P_R/|E_R|^2$ and $Q_R/|E_R|^2$ values are drawn, $P_S/|E_S|^2+jQ_S/|E_S|^2$ can be determined readily as co-ordinates of the intersection point of circles representing $P_R/|E_R|^2$ and $Q_R/|E_R|^2$ values applying to the particular problem. If Figure 3 is used as a separate chart, the additional use of the modified Evans and Sels chart, Figure 1B, is required to determine the voltage ratio necessary for the calculation of the sending-end power and for the determination of the power angle. It is apparent that the separate use of the chart of Figure 3 has no advantages over previous charts. However, if this chart is superimposed upon the modified Evans and Sels sending-end power chart, Figure 1A, what appears to be a useful new chart is produced.

This superposition is executed in Figure 4, using data and nomenclature of a previously published chart for easy comparison.[3] As can be seen, all receiving-end power circles intersect in the center of the $|E_R/E_S|$=constant circles. Since all circles P_R=constant, Q_R=constant intersect at right angles, the intersecting points are determined accurately. The chart is therefore more convenient to use than the synchronous-machine charts which it resembles.

The chart is equally useful in determining receiving-end quantities with sending-end quantities known, the steps being reverse of those indicated in the preceding problem. Essentially, the advantages of the Figure 4 chart are that power and voltage at either end can be determined from power and voltage at the other end by the use of a single chart, eliminating the transfer of points required on previous charts.

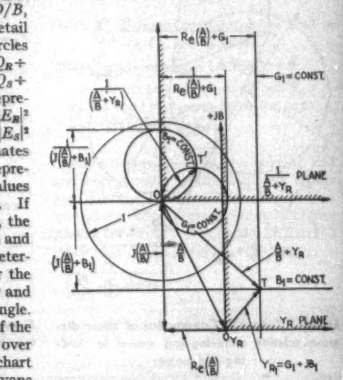


Figure 2. Complex inversion of Y_R+A/B

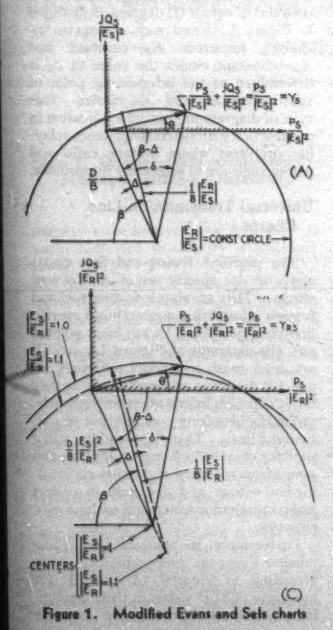


Figure 1. Modified Evans and Sels charts

In a similar manner Y_R can be expressed as a function of Y_S:

$$Y_R=\frac{\frac{P_R}{|E_R|^2}}{\frac{P_R+jQ_R}{|E_R|^2}}=-\frac{A}{B}+\frac{1}{B^2\left(\frac{\frac{P_S}{|E_S|^2}}{|E_S|^2}-\frac{D}{B}\right)} \quad (8)$$

A diagram similar to Figure 4 results, mapping the sending-end plane upon the receiver plane. Corresponding to the Evans and Sels diagrams, Figures 1C and 1D, two additional diagrams exist for the transformation of the $P_S/|E_R|^2=Y_{RS}$ plane into $P_R/|E_S|^2=Y_{SR}$ plane and vice versa. It will be sufficient to list the formulas for one of these transformations,

$$Y_{RS}=f(Y_{SR})$$

$$\frac{P_S+jQ_S}{|E_R|^2}=\frac{D}{B}\frac{|E_S|^2}{|E_R|^2}-\frac{1}{B^2\left(\frac{P_R+jQ_R}{|E_S|^2}+\frac{A}{B}\frac{|E_R|^2}{|E_S|^2}\right)} \quad (9)$$

The resultant diagrams are still circle diagrams, however, the circles do not intersect in one point. They have similar practical limitations as do the diagrams of Figures 1C and 1D.

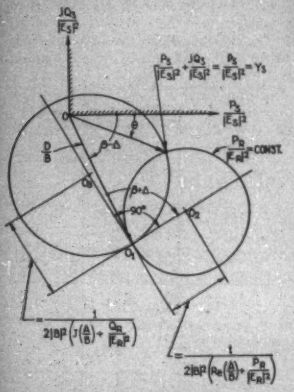


Figure 3. (above) Construction of circle diagrams relating receiving-end power to sending-end power

Circle Diagram for the Calculation of the Impedance at One End From the Impedance at the Other End

In conjunction with protection problems involving impedance relays with phase-angle control, circle diagrams relating impedances to $|E_R/E_S|$ and δ have found wide application.[7] These diagrams follow readily from equations 3, 4, 5, and 6. It will be sufficient to analyze but one specific case.

$$Z_S = \frac{1}{Y_S} = \frac{B}{\left(\frac{|E_R|}{|E_S|}/\underline{-\delta} - D\right)} \qquad (10)$$

Since Z_S is a linear fractional transformation of the independent complex variable $|E_R/E_S|/\underline{-\delta}$, straight lines and circles in the plane of the independent variable transform into circles in the Z_S plane. In particular, the circles $|E_R/E_S|$ = constant and the lines δ = constant transform into circles. Since the lines $|E_R/E_S|$ = constant and δ = constant are orthogonal, they will produce an orthogonal system of lines in the Z_S plane.[8] A similar diagram can be developed for the impedance Z_R. If it is required to determine the value of Z_S for a given value of Z_R, it is necessary to determine the values of $|E_R/E_S|$ and δ from the Z_R diagram and transfer the point to the Z_S diagram. This procedure is analogous to that required in the Evans and Sels diagrams.

In the following, circle diagrams will be developed for the direct determination of one impedance from the other, without transfer through the intermediate variables $|E_R/E_S|$ and δ. Since these diagrams closely resemble the admittance diagrams developed previously, it will be sufficient to consider one specific case, for instance, the mapping of Z_R into Z_S. Referring to equations 1 and 2, it follows:

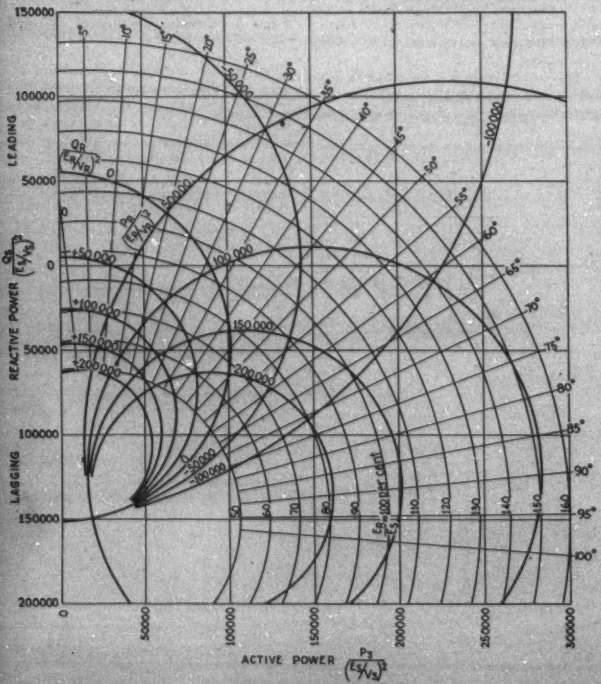
$$Z_S = \frac{E_S}{I_S} = \frac{AE_R + BI_R}{CE_R + DI_R} = \frac{AZ_R + B}{CZ_R + D}$$

$$= \frac{A}{C} - \frac{1}{C^2\left(Z_R + \frac{D}{C}\right)}$$

and with $Z_R = R_R + jX_R$:

$$Z_S = \frac{A}{C} - \frac{1}{C^2\left(R_R + jX_R + \frac{D}{C}\right)} \qquad (11)$$

Figure 4. Chart relating receiving-end power to sending-end power, voltage ratio, and power angle



As in the admittance diagrams where B = constant and G = constant lines mapped into circles, the foregoing equation transforms lines R_R = constant and X_R = constant into circles which intersect at one point. A particularly simple diagram results when the phase of the circuit constant C equals 90 degrees, as is shown in Figure 5. From such a diagram including numerous R_R = constant and X_R = constant circles the value of Z_S is determined as the intersecting point of appropriate R_R and X_R circles. This type of diagram might find application in conjunction with special impedance-relaying problems where voltage ratio and power angle are of secondary importance.

Universal Transmission-Line Charts

The modified Evans and Sels charts apply to one specific set of $ABCD$ constants. They are simple to construct and furnish information concerning a specific line very quickly. As has been pointed out, the diagrams of Figures 1A and 1B are used most commonly. Figures 1C and 1D diagrams are used rarely as they do not furnish information conveniently, ordinarily requiring construction of particular δ lines. There is, therefore, still a need for charts which furnish sending-end power from receiving-end power and sending-end voltage, and vice versa, in a direct and convenient manner, and without construction.

Furthermore, in planning new transmission lines, the preparation of charts according to Figures 1A and 1B for numerous $ABCD$ values is time consuming. Universal charts, giving data for

any line of arbitrary $ABCD$ constants, are preferred. Most of the existing charts, however, again require constructions to arrive at solutions. In the following, four charts similar to the Evans and Sels charts will be developed which will permit the quick calculation of power and voltage quantities for any $ABCD$ constants without construction and with a minimum of computation. These charts also will eliminate the shortcomings inherent to the charts shown in Figures 1C and 1D.

The principal handicap against the modified Evans and Sels charts being suitable for universal charts is the fact that each new value of B and D introduces a new distance and, more particularly, produces a change in angular relations. Different diagrams result even if $|D|$ and $|B|$ do not change, but Δ and β only. This suggests that the method used in Figure 1, representing the angular relations, should be modified, and that more emphasis should be placed on the

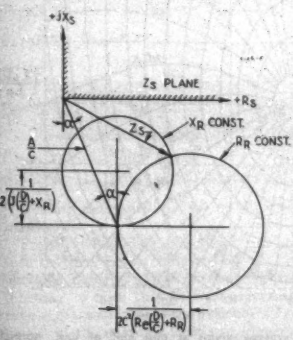


Figure 5. Diagram relating receiving-end impedance to sending-end impedance

angular co-ordinates. For instance, it seems indicated to identify sending-end power, not by $P_S=P_S+jQ_S$, but by $|p_S|$ and the power-factor angle θ_S. Furthermore, the power-factor angle θ_S is not as suitable as the angle ϕ_S to which it is related by $\phi_S=\beta-\Delta+\theta_S$. ϕ_S will be given preference in the following. In Figure 6A, the chart Figure 1A is reproduced with emphasis on these angular quantities. p_S is represented by $|p_S|=$ constant circles (only one shown) and $\phi_S=$constant lines (only one shown). As can be seen, each set of values δ and $|E_R/E_S|$ determines a corresponding set of values for $|p_S|$ and ϕ_S.

In the following chart, Figure 6B, a new orthogonal co-ordinate system for δ and $|E_R/E_S|$ is introduced with δ as abscissa and $|E_R/E_S|$ as ordinate. If the values of $|p_S|$ and ϕ_S corresponding to various values of δ and $|E_R/E_S|$ are deter-

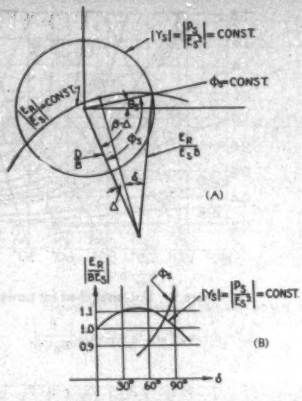


Figure 6. Transformation of conventional power diagram into E_R/E_S, δ diagram

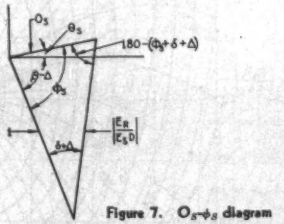


Figure 7. O_S-ϕ_S diagram

mined from Figure 6A and entered in Figure 6B, a useful chart results if the $|p_S|=$constant and $\phi_S=$constant lines are indicated. In this manner $|P_S|$ and ϕ_S can be determined for any given values of δ and $|E_R/E_S|$ and conversely. In order to arrive at a universal diagram, equation 3, representing Figure 6A, is divided by $|D/B|$, resulting in

$$p_S\left|\frac{B}{E_S^2D}\right|=-\left(\left|\frac{E_R}{E_SD}\right|\angle-\delta-1/\Delta\right)-\beta$$

Denoting the real quantity $|p_SB+E_S^2D|=O_S$, the Figure 7 diagram results, from which the following trigonometric relations can be established for the determination of the lines $O_S=$constant and $\phi_S=$constant in the $|E_SD/E_R|$, δ co-ordinate system:

$$\cos(\delta+\Delta)=\frac{1+\left|\frac{E_R}{E_SD}\right|^2-O_S^2}{2\left|\frac{E_R}{E_SD}\right|} \tag{12}$$

$$\left|\frac{E_SD}{E_R}\right|=\frac{\sin(\phi_S+\delta+\Delta)}{\sin\phi_S} \tag{12a}$$

Figure 8 shows the resulting plot covering a wide range of values. This chart

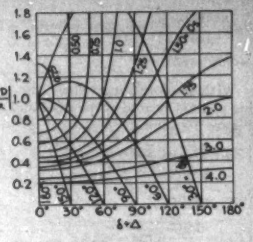


Figure 8. Universal transmission-line chart in E_R/E_S, δ co-ordinates

E_S and E_R in kilovolts

$\delta=$power angle between E_S and E_R

$\phi_S=\beta-\Delta+\theta_S$, $\theta_S=$power-factor angle

$O_S=(\text{kva})_S\times|B/E_S^2D|$

represents conditions at the sending end and corresponds to the modified Evans and Sels chart, Figure 1A. For the receiving-end chart corresponding to Figure 2A the following formulas can be derived when $|p_RB/E_R^2A|=O_R$, $\phi_R=\beta-\alpha+\theta_R$.

$$\cos(\delta-\alpha)=\frac{1+\left|\frac{E_S}{E_RA}\right|^2-O_R^2}{2\left|\frac{E_S}{E_RA}\right|} \tag{13}$$

$$\left|\frac{E_RA}{E_S}\right|=\frac{\sin(\phi_R-\delta-\alpha)}{\sin\phi_R} \tag{13a}$$

Comparison of equations 13 and 13a with equations 12 and 12a brings out the fact that identical plots are produced in slightly different co-ordinate systems. Figure 8 therefore could be used readily as receiving-end chart as well, with $|E_RA/E_S|$ as ordinate and $(\delta-\alpha)$ as abscissa. This feature brings out the inherent symmetry in the choice of the co-ordinates. In order to avoid confusion it appears advisable, however, to physically separate the two charts. Figure 9 shows one possible method suitable for practical use. The left-hand side of this chart is marked for receiving, the right-hand side for sending-end quantities. Figure 10 shows a section of chart of Figure 9 which covers the range of most common operating conditions. The use of these charts is illustrated best in conjunction with a practical example.

Given a transmission line with the following constants,

$A=0.917/1.06°=D$

$B=153/78.56°$

$C=0.00106/90°$

Determine sending-end power, power factor, and voltage if 75 megawatts at 99-per-cent power-factor leading is delivered at the receiving end at 154 kv.

Solution:

$(\text{kva})_R\cos\theta_R=(\text{kva})_R\times0.99=75$ megawatts; $(\text{kva})_R=75.75$ megavolt-amperes, $\theta_R=8.1°$

$$O_R = \frac{(\text{kva})_R}{154^2}\left|\frac{B}{A}\right| = 0.533, \quad \phi_R = 8.1° + 78.56° - 1.06° = 85.6°$$

With the foregoing values, the operating point is located in the left-hand side of Figure 10, giving

$$|E_R A/E_S| = 0.856$$
$$\delta - \alpha = 27.2°$$

from which

$$|E_S| = \frac{0.917}{0.856} \times 154 = 165 \text{ kv}$$

$$\delta = 27.2° + 1.06° = 28.26°$$

Next, computation of $|E_S D/E_R| = 165 \times 0.917/154 = 0.983$ and $\delta + \Delta = 29.32$ furnishes the operating point for the right-hand side of the Figure 10 chart, which corresponds to

$$O_S = 0.51 = \left|\frac{(\text{kva})_S B}{E_S^2 A}\right|$$

giving

$(\text{kva})_S = 83.1$ megavolt-amperes

$$\phi_S = 77.7 = \beta - \Delta + \theta_S$$

giving

$$\theta_S = -0.4°, \cos\theta_S = 1$$

From the foregoing example it can be seen that this universal chart furnishes the desired information quickly and with a minimum of calculations.

Whereas the charts in the first two sections of this paper were obtained as mappings of analytic complex functions, the universal charts are obtained by a purely geometrical process and do not represent such mappings. The orthogonal system of O_S = constant and ϕ_S = constant lines of Figure 7 does not map into an orthogonal system, as can be seen by inspection of Figure 9. An orthogonal system could be obtained if Figure 7 were mapped according to the function $1_S|E_R/E_S D|/\delta + \Delta$; however, this would produce a logarithmic scale for the ordinate which is less practical than the linear scale employed in Figure 9.

Charts of Figures 9 and 10 are applicable for the solution of problems where power and voltage at one end of the transmission line are given. Similar universal charts can be developed with power given at one end and voltage at the other. Since the derivation of the charts is similar to that of the preceding ones, it will be sufficient to list the relations corresponding to equations 12 and 13. The following notations and abbreviations are used in deriving them:

$$\phi_R = \beta - \alpha + \theta_R$$

$$O_{RS} = (\text{kva})_S \left|\frac{DB}{E_R^2}\right|$$

$$O_{SR} = (\text{kva})_R \left|\frac{AB}{E_S^2}\right|$$

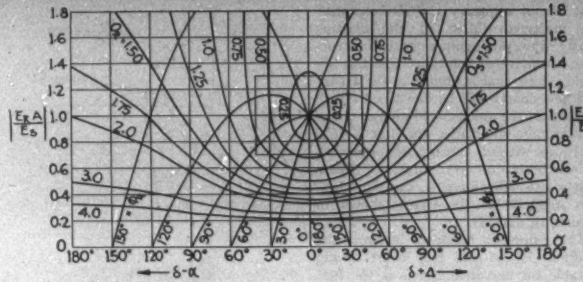


Figure 9. Universal chart for power and voltage given at one end of line

$$\phi_R = \beta - \alpha + \theta_R, \; O_R = (\text{kva})_R \left|\frac{B}{E_R^2 A}\right| \qquad \phi_S = \beta - \Delta + \theta_S, \; O_S = (\text{kva})_S \left|\frac{B}{E_S^2 D}\right|$$

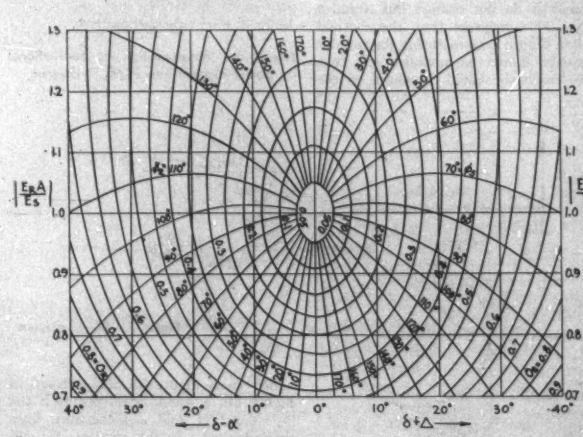


Figure 10. Universal chart for power and voltage given at one end of line, normal operating range

$$\phi_R = \beta - \alpha + \theta, \; O_R = (\text{kva})_R \left|\frac{B}{E_R^2 A}\right| \qquad \phi_S = \beta - \Delta + \theta, \; O_S = (\text{kva})_S \left|\frac{B}{E_S^2 D}\right|$$

resulting in

$$\cos(\delta + \Delta) = \frac{\left|\frac{DE_S}{E_R}\right|^2 + \left|\frac{DE_S}{E_R}\right|^4 - O_{RS}^2}{2\left|\frac{DE_S}{E_R}\right|^2} \tag{14}$$

$$\left|\frac{E_S D}{E_R}\right| = \frac{\sin(\phi_S + \delta + \Delta)}{\sin\phi_S} \tag{14a}$$

$$\cos(\delta - \alpha) = \frac{\left|\frac{AE_R}{E_S}\right|^2 + \left|\frac{AE_R}{E_S}\right|^4 - O_{SR}^2}{2\left|\frac{AE_R}{E_S}\right|^2} \tag{15}$$

$$\left|\frac{E_R A}{E_S}\right| = \frac{\sin(\phi_R - \delta + \alpha)}{\sin\phi_R} \tag{15a}$$

The resulting charts are shown in Figure 11, covering a wide range of values, and in Figure 12, applying to the normal operating range. Since appearance and use of the charts is similar to the previous ones, it will be sufficient to compute one example.

Referring to the afore-mentioned transmission line it is required to determine the receiving-end voltage and sending-end power when 50 megavolt-amperes at 90-per-cent power-factor lagging is delivered at the receiving end with the sending-end voltage maintained at 160 kv.

Solution:

As given,

$$\cos\theta_R = 0.90$$

therefore

$$\theta_R = -16.3°$$

$$\phi_R = \beta - \alpha + \theta_R = 78.56° - 1.06° + (-16.3°) = 61.2°$$

$$O_{SR}=(\text{kva})_R\left|\frac{BA}{E_S^2}\right|=\frac{51.2\times153.16\times0.917}{160^2}$$
$$=0.286$$

Referring to the left-hand side of chart Figure 12, the intersection of $\phi_R=61.2$ and $O_{SR}=0.286$ furnishes

$$|E_RA/E_S|=0.77$$

from which

$$|E_R|=\frac{0.77\times160}{0.917}=134.2 \text{ kv}$$

$$\delta-\alpha=19°$$

from which

$$\delta=19°+1.06°=20.06°$$

To find the sending-end power, compute

$$|E_SD/E_R|=\frac{160\times0.917}{134.2}=1.09$$

$$\delta+\Delta=1.06°+20.06°=21.12°$$

Referring now to the right-hand side of Figure 12

$$\phi_S=66.3° \quad O_{RS}=0.43$$

giving

$$(\text{kva})_S=\frac{0.43\times134.2}{153.16\times0.917}$$
$$=55 \text{ megavolt-amperes}$$
$$\theta_S=66.3°-78.56°+1.06°$$
$$=-11.2°, \cos\theta=0.981 \text{ lagging}$$

Sending-end power $55\times0.981=54$ megawatts.

From the foregoing example it can be seen that the desired information can be obtained quickly. It is particularly interesting to note that in this universal type of diagram none of the difficulties inherent in the modified charts of Figures 1C and 1D are encountered.

Additional data follow readily from these charts. The dotted line in Figure 10 indicates the optimum-power-limit line, corresponding to the envelope of the nonconcentric circles in the conventional diagram. This line corresponds to the line $O=1$ in Figure 10 and therefore can be constructed readily.

The power-limit parabola which is the locus of the maximum power transmitted at regulated potentials in the conventional diagram coincides with the constant-power-angle line where $\delta=\beta$.

Power-angle curves can be developed quickly from these charts.

Conclusions

1. A circle diagram is developed, relating power at one end to power at the other end.

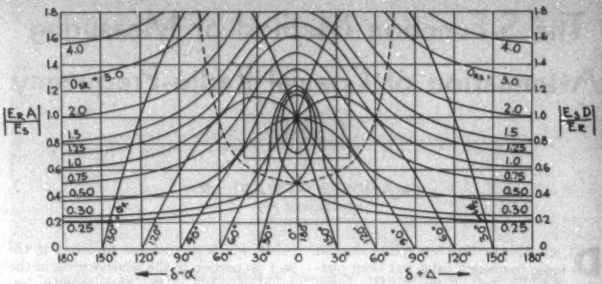


Figure 11. Universal chart for power given at one end and voltage at other end

$$\phi_R=\beta-\alpha+\theta_R,\ O_{SR}=(\text{kva})_R\left|\frac{BA}{E_S^2}\right| \qquad \phi_S=\beta-\Delta+\theta_S,\ O_{RS}=(\text{kva})_S\left|\frac{BD}{E_R^2}\right|$$

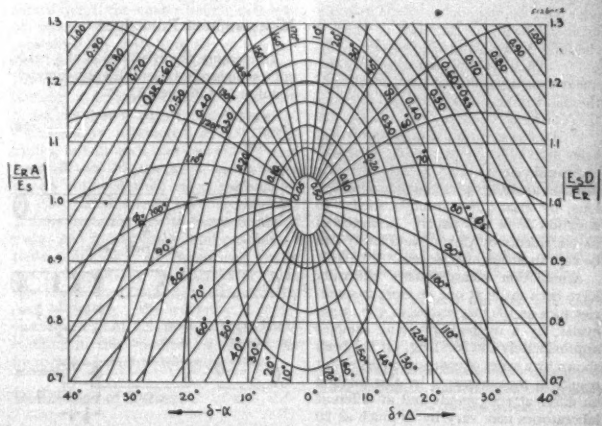


Figure 12. Universal chart for power given at one end and voltage at other end, normal operating range

$$\phi_R=\beta-\alpha+\theta,\ O_{SR}=(\text{kva})_R\left|\frac{BA}{E_S^2}\right| \qquad \phi_S=\beta-\Delta+\theta,\ O_{RS}=(\text{kva})_S\left|\frac{BD}{E_R^2}\right|$$

2. A circle diagram is developed, relating impedance at one end to that at the other.

3. Universal transmission-line charts are developed based on a new co-ordinate system from which the essential data pertaining to any line readily can be computed. The difficulty enountered in the conventional charts with power and voltage given at different ends is eliminated by this type of chart.

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The S-Function Method of Measuring Attenuation of Coaxial Radio-Frequency Cable

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DURING the last few years coaxial radio-frequency cable has been purchased in large quantities by the Army and the Navy for use in aircraft and surface vessels as radio and video transmission lines. Inspection of this cable has been carried out at the factories in accordance with the requirements of the applicable specifications, the latest of which is the Joint Army–Navy Specification *JAN-C-17*. These specifications require frequent measurements, at the factories, of the characteristic impedance and attenuation during production.

Characteristic impedance generally has been determined from results of capacitance and velocity of propagation tests on samples of cable approximately five feet long, by means of a formula similar to equation 32 of this paper. Accuracy of measurements by this method easily can be kept to within one per cent.

Attenuation measurements generally have been made at one or more frequencies such as 100 megacycles or 400 megacycles, by a method involving samples approximately 100 feet long. It has been shown by a series of comparison tests that results of measurements by this method on different equipments and at different laboratories may vary by as much as 20 per cent on one sample. This can be partially attributed to the use of nonstandard equipment and to the highly skilled technique required in making the measurements.

A new method of measuring attenuation, known as the *S*-function method, is here proposed. This method has been found to be simpler, faster, and more convenient than any other in general use. Also, it required samples which are shorter and the lengths of which are less critical than do other methods so far proposed. For example, the best length of radio-frequency cable *RG-8/U* for a 100-megacycle test is 11 inches. Although a knowledge of the characteristic impedance is required, an error in its value generally will not affect adversely the attenuation results, which is in contrast to some methods using resonant lengths of cable, which are subject to errors in direct proportion to the relative error in the supplied value of the characteristic impedance. This method, however, is limited by the design of presently available equipment to frequencies from about 1 to 100 megacycles.

Measurement Procedure

To measure the attenuation of a cable, cut a sample of total length approximately equal to (see Figure 1A)

$$d_s = \frac{144\,V}{f_{mc}} \text{ feet} \qquad (26)$$

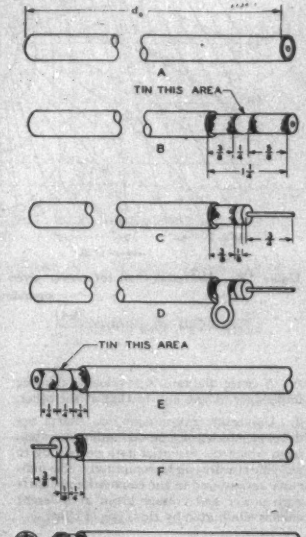

Figure 1. Preparation of the cable sample for measurement

where

V = relative velocity of propagation of cable
f_{mc} = test frequency in megacycles

Strip back outer covering for about 1¼ inches from one end and apply solder to the outside of the braid in a circular band as shown in Figure 1B. Cut through the braid and insulation to the inner conductor at about three-quarters inch from the end (Figure 1C), exercising care not to cut into the inner conductor. Solder a lug to the braid (Figures 1D and 3), making certain that a large part of the lug surface makes contact with the braid and that the entire region around the lug is well soaked in solder. An iron with about 200 watts capacity should be used. Strip back the covering at the other end of the sample for about three-quarters inch (Figure 1E), and soak solder into the braid in a circular band. Cut through the braid and insulation as shown in Figure 1F, and bend back the central strands radially and solder to the braid (Figures 1G and 3). It is important that each strand and this entire end of the braid be well soaked in solder to insure a low-resistance connection. It has been found that making only "spot" contacts has the effect of raising the values obtained for attenuation, N, by as much as ten per cent.

The prepared sample is connected to the Q meter (Figures 2, 5A, and 5B), which is operated in the usual manner for testing coils, and values of f, Q, and C recorded. These are applied to the solid curve of Figure 6 to obtain the value of S, which is inserted in the following formula for attenuation:

$$N = \frac{S}{Qd} \text{ decibels per 100 feet} \qquad (20)$$

As a guide in subsequent sample cutting, the dashed line of Figure 6 gives the ratio of preferred sample length (d_s) to the actual sample length (d).

At the lower frequencies it may become necessary to employ auxiliary capacitors. These should be of the silver mica type, and are connected to the "Cond" terminals of the Q meter. The amount of external capacitance required is determined easily from the fact that the total capacitance in micromicrofarads required to resonate a cable sample of length d_s will be

$$C_{\mu\mu f} = \frac{120{,}000}{f_{mc} Z_0} \qquad (29)$$

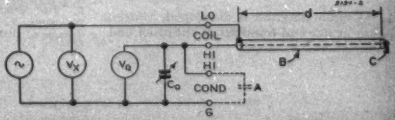

Figure 2. Schematic diagram of the measuring circuit

Standard Q meter such as Boonton type 160*A* or 170*A*
A—Auxiliary silver-mica capacitor as required
B—Cable sample under test
C—Inner conductor soldered to outer conductor at end

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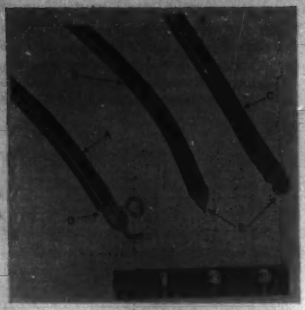

Figure 3. Prepared ends of cable samples for attenuation measurement

A. Radio-frequency cable *RG-8/U*
B. Radio-frequency cable *RG-7/U*
C. Radio-frequency cable *RG-8/U*
D. Connection to *Q* meter
E. Short-circuited ends of cable samples (should be well soldered in this fashion to insure minimum resistance and inductance)

where

f_{mc} = test frequency in megacycles
Z_0 = characteristic impedance of the cable in ohms

From equation 30 it may be noted that the lowest frequency at which 50-ohm cable can be tested on a type-160*A* Q meter without external capacitance is six megacycles.

Following is a typical example of data obtained in making an attenuation measurement on a sample of radio-frequency cable *RG-8/U*:

$d = 3.0$ feet
$Z_0 = 52$ ohms
$f_{mc} = 30$ megacycles
$Q = 89$
$C_{\mu\mu f} = 82$ micromicrofarads
$S = 274$
$N = 1.03$ decibels per 100 feet

Appraisal of the Method

A typical sample of coaxial cable, about 200 feet long, was tested at several government and commercial laboratories by various methods at 100 megacycles. The results are listed in Table I. It will be seen that the result obtained by the *S*-function method agrees closely with the average of the results of the other methods.

In Figure 7 results obtained on a sample of radio-frequency cable *RG-7/U* at frequencies from 1 to 100 megacycles by the *S*-function method have been plotted and compared with nominal values listed in the Joint Army–Navy Specification *JAN-C-17*. The measurement results lie almost in a straight line on "log–log" paper.

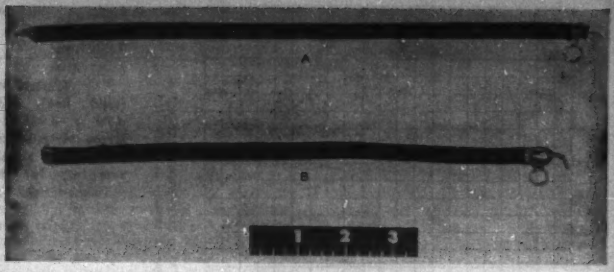

Figure 4. Cable samples prepared for attenuation measurement at 100 megacycles

A. Radio-frequency cable *RG-7/U* B. Radio-frequency cable *RG-8/U*

By use of equations 18 and 33 it can be shown that if the sample length, d, is held to within ten per cent of the length d_0, prescribed by equation 26, a ten-per-cent error in Z_0 will cause less than a two-per-cent error in attenuation, N, and likewise a 20-per-cent error in Z_0 will cause less than a six-per-cent error in N.

Tests were attempted at 200 megacycles, but in each case the results were from 10 to 15 per cent higher than values obtained from other methods or by extrapolation from lower frequencies. This is probably due to losses in the Q meter and its terminals, and possibly to some radiation. At frequencies below one megacycle, for most types of cable now in use, the Q values are too low to be read accurately. Consequently, it is recommended that for presently available equipment this method be limited to frequencies from 1 to 100 megacycles.

Definitions of Terms

α = attenuation constant of the cable sample in nepers per foot
β = wave-length constant of cable sample in radians per foot
$\gamma = \alpha + j\beta$
c = velocity of light in vacuum in feet per second = $983.57 \cdot 10^6$
C = distributed capacitance of cable in farads per foot
C_0 = capacitance required to resonate cable at test frequency in farads
d = length of cable sample in feet
d_0 = preferred length of cable test specimen in feet
ϵ = base of naperian logarithms
f = test frequency in cycles per second
G = distributed conductance of cable in mhos per foot
$j = \sqrt{-1}$
L = distributed inductance of cable in henrys per foot
$M = Z_0/X_{ac}$ introduced for convenience
M_0 = value of M for least error in N caused by an error in Z_0
N = attenuation of cable in decibels per 100 feet
P = power factor of the cable dielectric

Figure 5A. Connection of cable samples to Boonton type 160*A* *Q* meter for attenuation measurement by the *S*-function method at frequencies from 1 to 35 megacycles

1. Care must be taken that outer braid clears all metal except *LO* terminal by at least one-eighth inch
2. *LO* terminal
3. Connect silver-mica auxiliary capacitor to these terminals if required (usually unnecessary above six megacycles)

Figure 5B. Connection of cable sample to Boonton type-170*A* *Q* meter for attenuation measurement by the *S*-function method at frequencies from 35 to 100 megacycles

1. Care must be taken that outer braid clears all metal except *LO* terminal by at least one-eighth inch
2. *LO* terminal

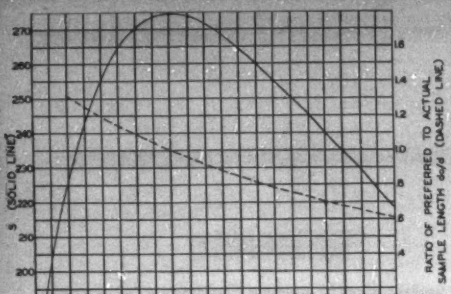

Figure 6. Plot of $S = \dfrac{2{,}000 \log_{10}\epsilon}{M+1/M+1/\text{arccot } M}$ **(solid line), and** $d_0/d = 0.923 +$ **arccot** M **= ratio of preferred to actual sample length (dashed line)**

$Q = X_{sc}/R_{sc}$

R = cable-conductor resistance in ohms per foot

R_{sc} = input resistance of short-circuited cable sample in ohms

S = function of M defined in equation 18 and plotted in Figure 6

V = ratio of velocity of radio-frequency potential in cable to velocity of light

ω = angular velocity of test voltage in radians per second

X_{sc} = input reactance of short-circuited cable sample in ohms

Z_0 = absolute magnitude of cable characteristic impedance

$\dot{Z}_0$ = complex cable characteristic impedance in ohms

$\dot{Z}_{sc}$ = input impedance of short-circuited cable sample, in ohms = $R_{sc} + jX_{sc}$

Derivation of Formulas

From fundamental transmission-line theory is obtained the following group of formulas[3]:

$$\alpha = {}^1/_2(G\sqrt{L/C} + R\sqrt{C/L}) \quad (1)$$

$$\beta = \omega\sqrt{LC} \quad (2)$$

$$\dot{Z}_0 = \sqrt{L/C}/{}^1/_2(G/\omega C - R/\omega L) \quad (3)$$

From basic capacitor theory[4]

$$G = P\omega C \quad (4)$$

$$P = G/\omega C \quad (4a)$$

If we divide equation 1 by equation 2,

$$\alpha/\beta = {}^1/_2(G/\omega C + R/\omega L) \quad (5)$$

Subtracting equation 5 from equation 4a yields

$$P - \alpha/\beta = {}^1/_2(G/\omega C - R/\omega L) \quad (6)$$

Combining equation 3 and equation 6 produces

$$\dot{Z}_0 = \sqrt{L/C}/P - \alpha/\beta \quad (7)$$

which, by definition, becomes

$$\dot{Z}_0 = Z_0/P - \alpha/\beta \quad (7a)$$

In practice $P \ll 1$ and $\alpha/\beta \ll 1$, so that the following approximation is accurate:

$$\dot{Z}_0 \cong Z_0[1 - j(P - \alpha/\beta)] \quad (7b)$$

From transmission-line theory:[5]

$$Z_{sc} = \dot{Z}_0 \tanh \gamma d \quad (8)$$

Substituting equation 7b in equation 8 yields

$$Z_{sc} = Z_0[1 - j(P - \alpha/\beta)](\sinh 2\alpha d + j \sin 2\beta d)/2(\cosh^2 \alpha d - \sin^2 \beta d) \quad (9)$$

As these tests are made on short lengths of cable such that $\alpha d \ll 1$, the following approximation of equation 9 is justified:

$$Z_{sc} = Z_0[2\alpha d - (P - \alpha/\beta)\sin 2\beta d - j \sin 2\beta d]/2 \cos^2 \beta d \quad (9a)$$

By definition and from equation 9a,

$$Q = X_{sc}/R_{sc} = \sin 2\beta d/[2\alpha d - (P - \alpha/\beta) \sin 2\beta d] \quad (10)$$

$$1/Q = (2\alpha d/\sin 2\beta d) - (P - \alpha/\beta) \quad (10a)$$

$$X_{sc} = Z_0 \sin 2\beta d/2 \cos^2 \beta d = Z_0 \tan \beta d \quad (11)$$

By definition and from equation 11,

$$M = Z_0/X_{sc} = \cot \beta d \quad (12)$$

$$\beta = (\text{arccot})\ M/d \quad (12a)$$

$$1/\sin 2\beta d = {}^1/_2\sqrt{2 + \tan^2 \beta d + \cot^2 \beta d} \quad (13)$$

If we combine equations 10a, 12, and 13,

$$1/Q = \alpha d\sqrt{2 + M^2 + 1/M^2} - (P - \alpha/\beta) \quad (14)$$

From equations 14 and 12a we obtain

$$\alpha = (1/Q + P)/d(M + 1/M + 1/\text{arccot } M) \quad (15)$$

$$N = (2{,}000 \log_{10}\epsilon)\alpha \quad (16)$$

so that

$$N = (1/Q + P)2{,}000 \log_{10}\epsilon/d(M + 1/M + 1/\text{arccot } M) \quad (17)$$

Let

$$S = 2{,}000(\log_{10}\epsilon)/(M + 1/M + 1/\text{arccot } M) \quad (18)$$

This is plotted in Figure 6. Then

$$N = S(1/Q + P)/d \quad (19)$$

American Society for Testing Materials specifications require polyethylene to have a power factor of less than 0.005 at 1 megacycle and at 100 megacycles. Measurements made on various samples of radio-frequency cable *RG-8/U* with

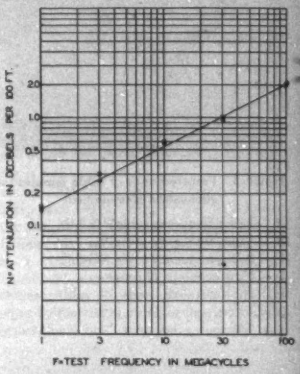

Figure 7. Results of attenuation measurements on radio-frequency cable *RG-7/U* by the *S*-function method (8) compared with engineering data listed in Joint Army–Navy Specification *JAN-C-17*, paragraph E-3 (X)

⊙ Results of S-function test on typical sample
× Engineering data listed in joint Army—Navy specifications

Q meters showed power factors of the order of 0.0002 at 10 megacyles and of 0.0003 at 100 megacycles. Consequently, for most work involving cables with this insulation, the assumption $P \ll 1/Q$ is justified, in which case equation 19 becomes

$$N = S/Qd \quad (20)$$

This assumption introduces an error in opposition to the effect of losses in the Q meter and cable-sample terminals, so that even in cases where P is as great as two or three per cent of $1/Q$, equation 20 in practice may yield results as accurate as does equation 19.

From equation 18 is obtained

$$1/S = (M + 1/M + 1/\text{arccot } M)/2{,}000 \log_{10}\epsilon \quad (21)$$

From inspection of equations 12, 19, and 21, it is seen that the value of d resulting in the least possible error in N introduced by a given error in Z_0 would result from the condition:

$$d(1/s)/dM = 0 \quad (22)$$

Solving equations 21 and 22 for M_0 yields

$$M_0 = \cot(M/\sqrt{1 - M}) \cong 0.7567 \quad (23)$$

From equations 23 and 12a, the length of cable which would give least error in N by an error in Z_0 is

$$d_0 = (\text{arccot } M_0)/\beta = 0.923/\beta \quad (24)$$

From fundamental theory,[5]

$$\beta = 2\pi f/Vc \quad (25)$$

so that equation 24 becpmes

$$d_0 = Vc(\text{arccot } M_0)/2\pi f = 144.5 \cdot 10^8 V/f \quad (26)$$

In the case of a cable with $V \leqq 0.65$, such as those with polyethylene or polyisobutylene dielectrics, this becomes about

$$d_0 = 94 \cdot 10^8/f \quad (26a)$$

For cables with air dielectrics, $V = 1.0$, in which case

$$d_0 = 144 \cdot 10^8/f \quad (26b)$$

If the measurement of X_{sc} is made on a Q meter,

$$X_{sc} = 1/\omega C_0 \quad (27)$$

from which, with equation 12,

$$M = Z_0\omega C_0 = 2\pi f Z_0 C_0 \quad (28)$$

and the setting obtained for the preferred length of cable will be, from equations 23 and 28,

$$C_0 = M_0/\omega Z_0 \leqq 0.12/fZ_0 \quad (29)$$

For 50-ohm cables, such as radio-frequency cable *RG*-8/*U*,

$$C_0 = 2{,}400 \cdot 10^{-6}/f \quad (29a)$$

Table I

Method	Laboratory	Decibels Per 100 Ft
Diode voltmeters at ends of long terminated sample[1]	E	1.65
	S	2.32
Tuned circuit-coupled-oscillator and diode voltmeter (most commonly employed at radio-frequency cable factories)	E	2.01
	T	2.13
	B	2.0
Short resonant lengths[3] (d = 19 in.)	S	2.14
(d = 38 in.)	S	2.17
(d = 59 in.)	S	2.14
The S-function method (d = 11 in.)	S	2.13

It will be found in practice that the lowest frequency at which tests by this method can be made on the type 160*A* Q meter without auxiliary capacitors is limited by the size of the tuning capacitor, whose highest usable capacitance is approximately 400 micromicrofarads. This frequency is given by equation 28, and for a 50-ohm cable would be

$$f = 2400 \cdot 10^{-6}/400 \cdot 10^{-12} = 6 \cdot 10^6 \text{ cycles per second} = 6 \text{ megacycles per second} \quad (30)$$

Obviously, the frequency range can be extended downward by connecting low-loss fixed capacitors to the capacitor terminals of the Q meter, so that the total capacitance at the center of the dial range will be approximately that given by equation 29.

From equation 7 and by definition of Z_0,

$$Z_0 = \sqrt{L/C} \quad (31)$$

which, with equations 2 and 25, yields

$$Z_0 = 1/VcC \quad (32)$$

From equations 12a and 24,

$$d_0/d = (\text{arccot } M_0)/\text{arccot } M \leqq 0.923/\text{arccot } M \quad (33)$$

This has been plotted as a dashed line in Figure 6.

Line Drop Produced by Resistance Welders

R. L. LONGINI
NONMEMBER AIEE

Synopsis: Resistance-welding machines normally form a very reactive pulsating load on a power system which sometimes produces undesirable line regulation. The regulation can be calculated, and, if it is too high, it can be reduced by operation directly on 2,300 volts or by power-factor-correction means. From a line-regulation point of view, the system of 2,300-volt operation is usually the most satisfactory. The effect of electronic controls on line drop is also discussed.

LARGE CURRENTS flowing across the junction between two metals evolve heat because of the contact and material resistance. Both the resistance and current are controlled in a resistance-welding machine so that the heat will be just right to produce a fusion weld. The contact resistance is controlled by proper surface cleaning and control of the contact forces by the welding machine. Current is controlled as to duration and magnitude by timing, heat-control circuits, and welding-transformer taps. The currents involved are very large, being between a few hundred and a few hundred thousand amperes, depending on the welding operation.

It is often necessary for mechanical reasons to have long arms on the welding-transformer secondary. This structure will have an inductance of the order of one microhenry. This inductance, although small, will be the main impedance to the welding current. In order to pass 10,000 amperes through this inductance at 60 cycles the transformer secondary must produce about four volts. The transformer will thus involve 40 kva just for this relatively small welding current.

Welding currents are normally of

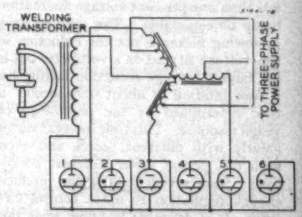

Figure 1a. Power circuit of three-phase to single-phase low-frequency converter

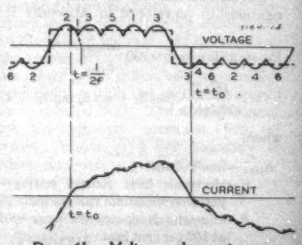

Figure 1b. Voltage and current waves

The solid lines are the actual voltage and current. The dashed lines are the values assumed in the mathematical analysis in the appendix. Numerals indicate which ignitrons are conducting

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4. THE RADIO ENGINEERS' HANDBOOK (first edition), F. E. Terman. 1943. Page 110.

5. Reference 3, page 145.

6. Reference 3, page 108, equation 23.

short duration. In production there ordinarily will be several pulses of current per second. This large, pulsating, low-power-factor (usually 0.25 to 0.4) single-phase load frequently requires a power system designed from a regulation point of view entirely without regard for thermal characteristics.

Line-Drop Calculations on Uncorrected Systems

The most common complaint occasioned by line regulation concerns light flicker. The eye is extremely sensitive to flicker if it occurs 2 to 12 times per second, less than one-per-cent voltage fluctuation being objectionable. The voltage drop producing flicker is not the reduction in rms voltage as read on a voltmeter but is the largest average reduction lasting for a time interval of about 0.02 second, a time determined by the physiology of visual response. This time interval varies greatly with different people and even with one person under different conditions. Some welder installations produce enough regulation to upset control circuits. It is desirable to know what the regulation will be for a system before installing a welder.

Regulation can be calculated by the relationship (developed in Appendix I):

$$\text{Per cent line drop} = 100\,\frac{\Delta E_{line}}{E_{line}}$$

$$= \frac{H^2 \cdot P}{100(kva)_{sc}}(\cos\theta_2 + \sin\theta_2 \tan\theta_1) \quad (1)$$

where

E_{line} = line voltage
H = electronic heat control setting = per cent maximum rms current
P = kilowatts dissipated during a weld at 100 per cent heat
$(kva)_{sc}$ = short-circuit kilovolt-amperes of power-supply system
θ_1 = phase angle of total circuit impedance
θ_2 = phase angle of power system impedance

A given welding operation will require a certain value of the kilowatts, P, dissipated during the weld. It is of interest, however, to see how the other parameters enter into the line drop. The power factors or impedance phase angles enter into the line drop critically. The phase angle of the power system, θ_2, is normally between 60 and 85 degrees so that the term $\sin\theta_2 \tan\theta_1$ is of primary importance in this factor. The total impedance of the circuit is largely that of the load so that θ_1 is almost entirely determined by the load power factor. The phase angle θ_1 is usually greater than 65 degrees, thus a slight improvement in power factor may reduce the line drop very greatly as the tangent varies rapidly in this region. Since low-load power factor is largely due

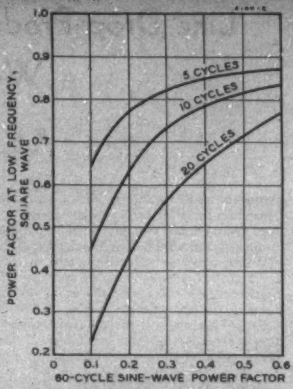

Figure 2. Comparison of the power factor at 60-cycle operation with the power factor of the same machines at low-frequency square-wave operation

to the inductance of the secondary loop, the loop should be designed with as low an inductance as is compatible with other considerations.

It is apparent from the formula that it is desirable to have the short-circuit kilovolt-amperes of the power system, as seen from the welder, as large as possible. On low-voltage power systems the short-circuit characteristics are determined largely by the step-down transformers which limit the short-circuit current greatly. This limitation is avoided and the short-circuit kilovolt-amperes greatly increased by working directly from the high-voltage distribution lines. Welder controls for direct operation on 2,300-volt distribution systems are now available. Operation from these may be direct or may be through a transformer used for the individual welder only in which case the step-down transformer should be considered to be a part of the welding system. Line drop for 2,300-volt operation may be as little as ten per cent of its value for low-voltage operation. Though 2,300-volt operation is usually desirable it is not always possible. Some power-factor-correction means therefore may be required.

Low-Frequency Systems

Certain electronic frequency-changing circuits draw almost balanced three-phase power from the line and have a low-frequency single-phase output. Because power factor is increased when the load is operated at low frequency a double advantage can be had from such an electronic circuit. There are a number of circuits, all fundamentally alike, designed to produce single-phase low-frequency power from a polyphase system. By a

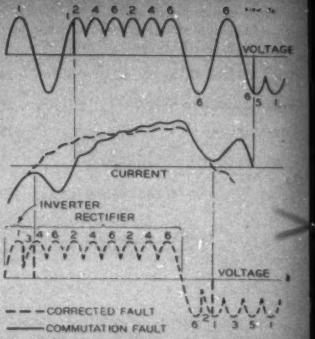

Figure 3a. Current and voltage waves for corrected and uncorrected commutation faults

Numerals indicate which ignitrons of Figure 1a are conducting

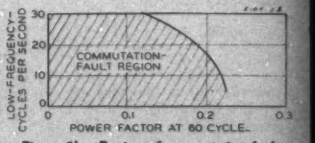

Figure 3b. Region of commutation fault

system of rectifiers, current is first passed through the load in one direction, then, after one-half cycle of low frequency, the current is passed through the load in the opposite direction.

Figure 1 shows a circuit for three-phase to single-phase conversion with resultant voltage and current waves. The low-frequency voltage wave can be approximated very closely by a square wave plus some high harmonics. The current wave will have these harmonics but only to a very slight degree due to relatively high reactive impedance to these high frequencies. The power factor and other properties of the secondary loop resulting from low-frequency operation can be calculated. (See Appendix II.) The power factor of the entire welder depends on the type of rectifier and the regulation of the transformer involved. Figure 2 shows power-factor curves for a low-frequency welding system having good transformer regulation, being used at full heat. Heat control, which involves delaying the ignition of the rectifier ignitrons, reduces the power factor greatly.

Voltage and Current Reversal

Each ignitron carries current until another ignitron with properly applied voltage takes over this task or until the load current becomes zero. When it is desired to reverse the voltage no subsequent ignitron is fired to which the current can

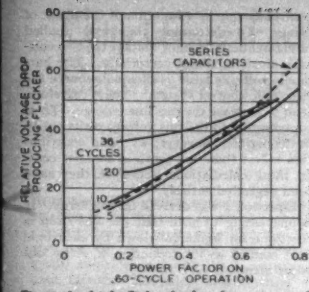

Figure 4. Light flicker for low-frequency and series-capacitor systems compared with 60-cycle uncorrected systems (equal 100 on voltage scale)

The voltage drop producing light flicker depends on the physiology of the eye

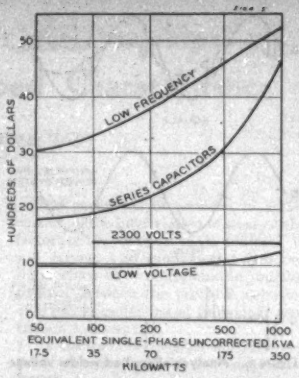

Figure 5. Cost of controls for various systems having a resistance-to-inductance ratio giving 35-per-cent power factor at 60 cycles

commutate so that the last ignitron fired in each voltage pulse carries current until the current ceases.

Before the last ignitron extinguishes, the voltage of the corresponding rectifier-transformer secondary winding reverses. The current is then flowing against the applied voltage and is quickly reduced in magnitude, but continues to flow against the applied voltage because of the reactive nature of the load. When the current finally reaches zero the ignitron extinguishes. The operation can best be seen by referring to Figure 1b. Tube 3 is the last tube to be fired in the upper portion of the voltage wave shown. It continues to carry the current until time t_0, at which instant the current is zero. At that time, or very shortly thereafter, tube 4 is ignited. This tube applies the voltage to the loop in such a way as to reverse the direction of the current. The subsequent firing order is shown in the figure.

If the load is so reactive that $t_0 > 1/120$ second, the rectifier transformer voltage again reverses and the current will be built up again instead of being reduced to zero. Therefore the ignitron will continue to conduct. This condition, known as a commutation fault, is shown in Figure 3a. The boundary of the commutation-fault region (calculated in Appendix II) is shown in Figure 3b.

Commutation Fault and Limitations and Correction

Commutation fault introduces drawbacks to the use of low-frequency systems. During one or more cycles (on supply-frequency basis) the entire load is single phase, resulting in a momentarily increased voltage drop of two lines. Though this momentary drop will have a very small value when read on an rms meter it may cause objectionable light flicker. The drop that must be considered is the drop on the loaded phase lines.

It is possible to avoid commutation fault by a different method of operation. Refer again to Figure 3a. The dashed curve shows a system corrected for commutation fault. At the time tube 3 (left of the corrected-voltage-wave, lower part of the figure) is fired, its anode is more positive than that of tube 1 so that the current can commutate to it readily. Very shortly after the commutation is completed, however, the applied anode voltage of tube 3 goes negative, thus the current continued to be opposed. This process is repeated until the current reaches zero. The operation described is that of an inverter. Power from the reactive energy of the electrode loop has thus been fed back into the power-distribution system. After the current reaches zero, the system is again operated as a rectifier. This inverter–rectifier operation eliminates any single-phase operation such as occurs during a commutation fault. The power-factor-correction curves of Figure 2 are based on this inverter–rectifier system.

Series-Capacitor Systems

The power factor of a welder can be corrected by inserting capacitors in series with its primary winding. The capacitance is of such a value that it tunes to resonance, or close to it, with the inductance of the welding transformer. Thus the capacitor and welding transformer in series have no 60-cycle reactive component. The current is limited entirely by the reflected resistance of the welding-transformer secondary winding.

At full heat a series-capacitor-corrected welder operates on unity power factor. When reduction of current by electronic heat control is used, the ignitrons are fired later in the cycle than at 100 per cent heat. This makes the 60-cycle component of current lag behind the line voltage, therefore making the load appear reactive. Because the current is large at 90 per cent heat and is lagging behind the line-voltage the regulation is actually greater than at 100 per cent heat. As the heat is reduced below 90 per cent the regulation improves.

The inductance of the system may be altered by adjusting the secondary loop for different welding operations, or, very slightly, by varying the amount of iron in the secondary loop. Any large inductance changes require readjustment of the capacitor bank if perfect power-factor correction is desired.

Light-Flicker Comparisons

Figure 4 compares the light flicker produced by series-capacitor and low-frequency systems with the flicker resulting from uncorrected-power-factor systems. The curves are based on a power line with 0.3 power factor. Series capacitors correct the power factor completely at 100 per cent heat, but when the ignition is delayed harmonics are introduced which destroy this perfect correction. As a result, maximum line drop occurs at about 90 per cent heat, for which the series-capacitor curve is shown. The drop produced by the low-frequency system was on the basis of full heat. At reduced heat the system utilization is poor and rectifier power factor differs very appreciably from unity so that the greatest drop will be at reduced heat. The drop produced by low-frequency operation will, of course, pulsate at a low frequency to which the eye is very sensitive.

Metallurgical Considerations in Power Factor Correction Problems

Power-factor correction alters one metallurgical factor, the heat generated at the weld being dependent in a different way on work resistance. A slight change in resistance at the weld on uncorrected systems has only a very slight effect on the current as the current is largely inductively limited. In the low-frequency system the current is almost entirely resistance limited. In series-capacitor circuits the welding transformer gets its voltage by virtue of a resonant condition, the primary voltage on the welding transformer being, as a result, approximately inversely proportional to secondary resistance. The secondary current is thus dependent on secondary resistance as it is in low-frequency systems.

The resistance of the work depends on surface conditions, electrode pressure, and materials being welded. The power delivered to the spot, I^2R, will vary with the work resistance depending on how the current varies with resistance. In low-power-factor uncorrected systems, where

the weld current is independent of resistance, the power dissipated at the weld is directly proportional to the weld resistance. In corrected systems the heating is inversely proportional to the secondary resistance. The quality of the weld is determined to a large extent by the power dissipation at the spot and therefore on the power factor of the welding machine.

Cost

Both the low-frequency systems and the series-capacitor systems are expensive. The cost depends on many factors, among them: duration of "on" and "off" periods, power factor before correction, type of control, and power required. Figure 5 shows how the cost of the controls varies. The cost is dependent on the power factor before correction and on the power demand. To put the systems on a comparative basis, the power demand is plotted as that for an equivalent uncorrected system.

Conclusions

The line drop of a system can be readily calculated for a given welder. If the line drop turns out to be too great there are several alternatives possible to reduce it, the most satisfactory and least expensive usually being operation on 2,300 volts.

Not only power line but also welding properties must be considered in determining the desirability of using a power-factor-correction system. The dependence of power dissipated at the weld on the power factor is pronounced. No general statement can be made as to the most desirable power factor but it should be pointed out that power-factor correction may be, on some jobs, very undesirable from a welding point of view. Depending on the welding job it might be desirable or undesirable to use power-factor-correction systems.

Series-capacitor systems are less expensive than low-frequency systems for the same improvement in light flicker and kilovolt-ampere demand, though they are still single phase. If the welding loop is to be varied appreciably in any dimension there must also be adjustments of the series capacitors if perfect power-factor correction is to be maintained. Low-frequency systems do not require readjustment with change of the welding loop, but may be subject to commutation fault.

Appendix I. Voltage Drop for Single-Phase Uncorrected-Power-Factor Electronically Controlled Welder

An oscillogram of the voltage and current waves of a heat-controlled wave appear as shown in Figure 6a. The inductive nature of the load causes the current to continue to flow even after the voltage has reversed in direction. It will be noted, on examination of the voltage wave, that it is the sum of the two voltages shown in b and c of Figure 6. Figure 6b is the voltage supplied by the power system and Figure 6c is the voltage generated by the electronic controls. By this division of the electromotive force it is possible to treat the circuit as though it were composed entirely of linear impedance elements. The circuit then has two voltage sources, the power system and the electronic-control system, as shown in Figure 7a.

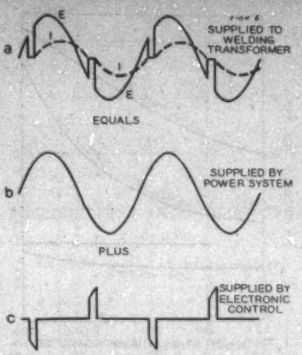

Figure 6. Analysis of applied welder voltage

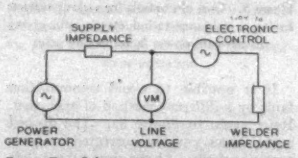

Figure 7a. Schematic circuit with assumption of linear elements

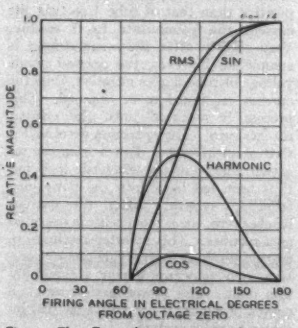

Figure 7b. Typical output of electronic generator

Supply voltage = −1.0

The voltage generated by the electronic-control system, though very rich in harmonics, has a considerable line-frequency component. Figure 7b shows an analysis of the voltage generated by the electronic-control system as a function of the phase of firing. To determine the total applied fundamental-frequency voltage the two voltages must be added vectorially. The harmonic voltages have as their sole source the electronic-control system. They, therefore, tend to increase the rms line voltage. Their contribution to the rms voltage turns out to be negligible, however, as their contribution is less than one tenth of one per cent. In these calculations, therefore, they have been neglected entirely.

Equation 1 was derived on this basis. It is interesting to note that the line drop is the same for input cut down by electronic heat control as for reduction of P by tap adjustment.

Appendix II. Calculation of Three-Phase to Single-Phase Low-Frequency Welder Characteristics

Calculations of power factor on the basis of a perfect square-wave generator. Actual power factors may be only 60 per cent of F_f.

$$F_f = \text{kw/kva} = 1{,}000P/VI_{rms} \qquad (2)$$

where

F_f = power factor at low frequency, f
P = kilowatts
V = square-wave voltage
I_{rms} = low-frequency rms current

$$I_{rms}^2 = \frac{1{,}000P}{R_f} \qquad (3)$$

where

R_f = resistive component of low-frequency impedance

$$F_f = \frac{I_{rms}R_f}{V} \qquad (4)$$

The current resulting from the square voltage wave will have an exponential form for each half cycle given by

$$i = \frac{V}{R_f}\left[1 - \frac{2\epsilon^{-at}}{1+\epsilon^{-a/2f}}\right] \qquad (5)$$

Where f is the square-wave frequency, a is the R/L ratio of the secondary loop and is given by

$$a = 377\left(\frac{1}{F_\infty^2} - 1\right)^{-1/2}$$

where F_∞ is the power factor for the given R/L ratio when operated on a 60-cycle sine-wave voltage. The time t is measured from the instant of voltage reversal.

From the definition of I_{rms}

$$I_{rms}^2 = \frac{2fV^2}{R_f^2}\int_0^{\frac{1}{2f}}\left[1 - \frac{4\epsilon^{-at}}{1+\epsilon^{-a/2f}} + \frac{4\epsilon^{-2at}}{(1+\epsilon^{-a/2f})^2}\right]dt \qquad (6)$$

Evaluation of the integrals gives

$$I_{rms}^2 = \frac{2fV^2}{R_f^2}\left[\frac{1}{2f} - \frac{4}{a}\frac{1-\epsilon^{-a/2f}}{1+\epsilon^{-a/2f}} + \frac{2}{a}\frac{1-\epsilon^{-a/f}}{(1+\epsilon^{-a/2f})^2}\right] \qquad (7)$$

Coincidence-Factor Relationships of Electric-Service-Load Characteristics

CONSTANTINE BARY
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Synopsis: This paper contains a demonstration of the existence in practice of relationships between group coincidence factors and number of consumers, and between group coincidence factors and consumers' load factors. Empirical relationships developed from test observations are analyzed from theoretical considerations, formulated in a general manner, and qualified as to the significance of the quantitative values.

THE STUDY of electric-service loads may be divided into two major parts; one dealing with the gradual ebb and flow of loads which are integrated over specified intervals of time measured in terms of minutes, and the second dealing with momentary surges of load which last for short intervals of time measured in terms of seconds. The load characteristics of each of these parts in turn may be subdivided into four distinct components; one taken as at the terminals of the individual appliances and applications, the second one as at the service entrance of individual consumers of electric service, the third one for the diversified conditions of groups of consumers or groups of specified appliances and applications, and the fourth for all classes of consumers or for all classes of appliances and applications, which results in what may be called the "system" conditions.

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This paper will be confined to a discussion of the interrelation of some of the factors of the first part of the subject. It will outline two fundamental relationships which have been found in practice to exist between the probable behavior of coincidence factors of individual consumers' loads and

1. A change in the number of consumers.
2. A change in their individual load factors.

These basic relationships were selected for this paper because they have the greatest significance in the engineering and economic features of central-station supply and because comparatively little is known of their probable behavior.

Diversity factor, which is a measure of the degree of diversity present between maximum loads of individual parts of a system, is defined by the AIEE as "the ratio of the sum of the maximum power demands of the subdivision of the system or part of the system to the maximum demand of the whole system or part of the system under consideration measured at the point of supply." For purposes of this discussion, however, it will be easier to visualize and deal with the reciprocal of this relation, that is, with the coincidence in maximum power demands. Its measure is expressed as a "coincidence factor" and will be defined as the ratio of the maximum coincident total power demand of a group of consumers to the sum of the maximum power demands of the individual consumers comprising the group, both taken at the same period of time.

While the diversity factor can never be *lower* than unity, the coincidence factor can never be *greater* than unity and, therefore, in dealing with the coincidence factor, we deal in values between zero and unity, while in the case of diversity factor we deal in values between unity and infinity. Since a large part of the facilities required to render electric service depends upon the coincident or diversified maximum demands of groups of consumers, it is evident from the foregoing definition that the higher the coincidence factor, the larger becomes the amount of facilities required per kilowatt of the non-coincident maximum demands of individual consumers, and the lower the coincidence factor, the smaller it becomes.

Major Factors Affecting the Coincidence in the Use of Service

The manner in which electric service is used by individual consumers or groups of consumers, and thus the degree of coincidence in this use, is determined by many factors. Among the more important ones may be mentioned population habits, community and business practices, weather and other climatic conditions, design of utilization equipment, and methods employed in the control of use of the service rendered. The significance of these factors may become clearer from the following discussion.

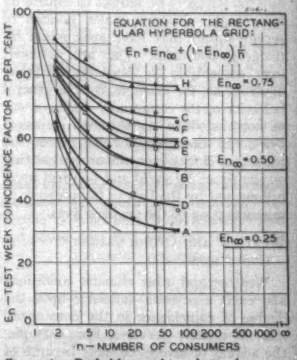

Figure 1. Probable trend in relation between group coincidence factor and number of consumers in group

Based on one-half-hour integrated demands in December reflecting 1938 and 1939 test data, and for a range in average of consumers' monthly load factors, as follows:

Domestic, without electric ranges:
A—12-per-cent load factor
B—23-per-cent load factor
C—31-per-cent load factor

Domestic, with electric ranges:
D—10-per-cent load factor
E—16-per-cent load factor

Retail light and power, industrial:
F—17-per-cent load factor

Retail light and power, commercial:
G—18-per-cent load factor
H—28-per-cent load factor

but

$$\frac{1-\epsilon^{a-/f}}{(1+\epsilon^{-a/2f})^2}=\frac{1-\epsilon^{-a/2f}}{1+\epsilon^{-a/2f}}=\frac{\epsilon^{a/4f}-\epsilon^{a/4f}}{\epsilon^{a/4f}+\epsilon^{-a/4f}}$$

$$=\tanh\frac{a}{4f}$$

Therefore, by equations 4 and 7

$$F_f=1-\frac{4f}{a}\tanh\frac{a}{4f} \qquad (8)$$

Calculation of Commutation Fault

A commutation fault occurs if i_0, the time for the current to reach zero after voltage reversal, is greater than $^1/_{120}$ second.

From equation 5

$$i=0=\frac{V}{R_f}\left[1-\frac{2\epsilon^{-a/t_0}}{1+\epsilon^{-a/2f}}\right] \qquad (9)$$

For $t_0 > {}^1/_{120}$ second, the condition of commutation fault,

$$\epsilon^{a/120}(1+\epsilon^{-a/2f})<2 \qquad (10)$$

or

$$a<84 \qquad F_m<0.22$$

A fault occurs if inequality 10 holds.

Population Habits and Community and Business Practices

Population habits and community and business practices exert a powerful influence upon the degree of coincidence in the consumers' use of electric service. The difference in the time when people get up; when they go to bed; how, when, and what they eat; where they live; the holidays they observe; where, when, and at what they work; the amount of leisure they have; and, generally speaking, how they live, work, and play on different days of the week and in different seasons of the year; all of this is reflected in the degree of coincidence of consumers' use of electric service. These conditions are not subject to precise mathematical formulations, and their resultant effect will be different for different communities and different climatic, social, and political conditions. But for any given community, operating under a given set of social and political conditions, the resultant effects of population habits and community and business practices upon the manner of use of electric service usually fall into some general pattern and thus result in some determinable values of the degree of coincidence of individual consumer's use of service. These forces are generally too strong to be subject to control by individuals, although major policies of service-supply may have some minor influences upon them. They are, however, very susceptible to social and political controls, as, for example, by the general behavior of the community during a war as contrasted to its behavior in peacetime; by the artificial changes in the setting of clocks from the normal setting on sun time; by social and political revolutions and by the lack or the presence of regimentation of the people's lives.

Weather and Other Climatic Conditions

Weather and other climatic conditions also exert a powerful influence upon the degree of coincidence in the consumers' use of electric service. For example, the advent of severe darkness because of an oncoming storm during otherwise daylight hours may create a full coincidence of the power and lighting loads, wiping out the normal diversity between their individual maximum demands and thus increasing the coincidence factor. A severe cold spell causing the almost continuous operation of individual heating plants increases the extent of coincidence in the use of electric service in connection with such plants. A severe hot spell, causing an almost continuous operation of individual air-conditioning plants and other forms of cooling and ventilating equipment, increases the extent of coincidence in the use of electric service in connection with these appliances. These forces are beyond the control of individuals. They are not subject to exact mathematical determinations. But they are susceptible, in general, to appraisals from available weather records for average, maximum, and minimum conditions.

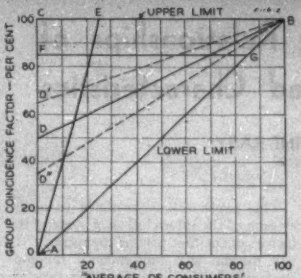

Figure 2. Illustration of the significance of certain lines on chart of coincidence factors versus consumers' load factors

Design of Utilization Equipment

The design of utilization equipment has a considerable influence upon the degree of coincidence of consumers' use of electric service. For example, generally speaking, to perform a given task through expenditure of a given amount of energy, devices which are "overcapacitied" may have lower coincidence factors than devices which are "undercapacitied," although the coincident maximum demand of the former may be higher than the coincident maximum demand of the latter. Devices designed for full automatic operation under intermittent cycles may have lower coincidence factors than those designed to accomplish the same purpose under manual operation. These design features are well within the control of design engineers, although it should be realized that the effects of different designs cannot be ascertained from laboratory tests, but must be obtained from extensive research and tests of sample applications in actual use.

Methods of Control

Methods for artificial control in the use of service also have important influences upon the degree of coincidence of consumers' demands. Generally speaking, a group of identical devices operating without any restrictive control will experience a smaller coincidence in their individual maximum demands than the same group of devices operating under a predetermined control cycle, even though the group of uncontrolled devices may possess features which are undesirable from other considerations affecting the system while the controlled devices may not have such undesirable features.

Notwithstanding the complexity of forces which affect the degree of coincidence in the use of electric service, experience has demonstrated the existence of two general phenomena relative to the behavior of group coincidence factors. One is the relationship between group coincidence factors and the number of consumers in a group, and the other, which only recently has received closer attention, is the probable relationship between group coincidence factors and average load factors of individual consumers of a group. These constitute the two basic coincidence-factor relationships of electric-service-load characteristics and are of fundamental significance in central-station service supply. They find applications in engineering and economic studies dealing with load forecasting for system planning, design of distribution systems, provision of service facilities, development of utilization appliances and applications, determination of cost to serve for widely different characteristics of service requirements, design of rates, and determination of service-sales-promotion policies for best economic results.

Coincidence Factor Versus Number of Consumers

In a general way the coincidence-factor-versus-number-of-consumers relationship may be formulated as follows:

For consumers of equal size, with no artificial restrictions placed in the way of their service use, and with all other things equal, the degree of coincidence of the maximum power requirements of a group of consumers decreases along a path resembling that of a rectangular hyperbola from unity for one consumer in a group to values approaching the asymptote of the rectangular hyperbola for an infinite number of consumers in a group.

Figure 1 depicts a mathematical grid of the simplest equation for a rectangular hyperbola and demonstrates that the results of actual test observations for various types of consumers of the domestic, commercial, and industrial classifications in general follow the mathematical relationships of the assumed empirical equation reasonably well. It also illustrates two very important conditions present in this relationship in practice: first, that the convergence of the relationship toward the asymptote is comparatively rapid for all values of E_{n_c} indicating that beyond 100 consumers in a group the change in coincidence factors is relatively small, and, secondly, that the convergence to the asymptote is more rapid for the higher values of E_{n_c} than for the lower ones.

The practical significance of these conditions is found in the fact that statistically stable results, as to diversified-load characteristics, may be expected in the practical range of E_{n_c} when as few as 100 consumers are involved in any one group, and results of sufficient engineering stability can be obtained even from

groups of only 30 to 50 consumers for values of E_{a_m} of 20 per cent and higher.

Coincidence Factor Versus Load Factor

The subject of the probable behavior of coincidence factors of groups of consumers with a change in their individual load factors only recently received closer attention throughout the electric-utility industry. In the past there existed a feeling among students of this problem that, in a general way, the extent of coincidence in time of the load requirements of a group of consumers of electric service ordinarily increases as the load factors of the individual consumers of a group increase. But, in general, the practical nature of the relationship was not known. It was in 1937 that the author first demonstrated the existence of a probable relationship between coincidence factors and individual load factors of groups of consumers over the complete load-factor range.[1] Subsequently it has been studied, in a thorough manner, by a subcommittee (F. M. Terry, chairman)[2] and H. E. Eisenmenger rationalized and verified the shape of the author's original empirical curve, in a classical manner, from mathematical considerations.[3] The following discussion will elaborate upon some of the more important theoretical aspects of this subject and will expand upon the author's original findings in the light of new and additional information secured since the original demonstration of the relationship.

Theoretical Considerations

It is obvious that a group of consumers, each having a 100-per-cent load factor, has a coincidence factor equal to unity. Furthermore, it may be demonstrated that a group of many consumers, each having a load factor approaching zero, and being unrestricted in the manner of operation throughout the entire period under consideration, will have a coincidence factor which will approach the value of one divided by the number of consumers, and which will approach zero for small demand intervals and for a very large number of consumers in a group. Thus, with the two extreme values known, it may be expected that, for a large number of consumers and under natural conditions of load behavior, there will exist some probable relation which will connect these two points.

It also may be demonstrated that under no condition can the value of the coincidence factor of a group of consumers, each having the same load factor, drop below the load factor, nor can it, by definition, exceed the value of unity. With these limits set, the probable relations should lie between these limits marked *AB* and *CB* in Figure 2. Theoretically, of course, for any given value of consumers' load factors, the group coincidence factor can have any value between these limits.

From theoretical considerations of an equal probability in the influence of the two limits upon the coincidence factor of a group of consumers with a given load factor, one may expect to find the path of the probable relationship to follow the line *BD* whose points for a given load-factor value will be equidistant from the limits of the possible relationships depicted by lines *AB* and *CB*. Straight lines emanating from *B* above or below line *BD*, for example, line *BD'* or *BD''*, produce relationships with unequal weights in the probability of the influence of the upper and lower limits upon a given group coincidence factor, the line above the line *BD* giving greater weight to the influence of the upper limit, and the lines below giving greater weight to the influence of the lower limit.

Actual experience has demonstrated, however, that the most probable relationships between group coincidence factors and individual consumers' load factors do not follow the straight lines depicting certain predetermined and constant relative weighing of the values of the upper and lower limits over the entire range of

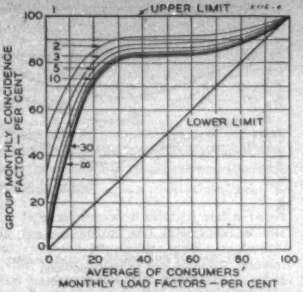

Figure 4. Empirical trend in the relation between coincidence factor and load factor for different numbers of consumers in group

Based on one-half-hour integrated demands in December

Numbers affixed to curves indicate number of consumers in group

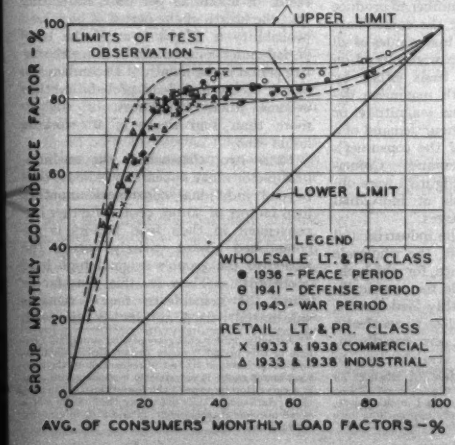
UPPER LIMIT
LIMITS OF TEST OBSERVATION
LOWER LIMIT
LEGEND
WHOLESALE LT. & PR. CLASS
● 1936 - PEACE PERIOD
⊖ 1941 - DEFENSE PERIOD
○ 1943 - WAR PERIOD
RETAIL LT. & PR. CLASS
× 1933 & 1938 COMMERCIAL
△ 1933 & 1938 INDUSTRIAL
GROUP MONTHLY COINCIDENCE FACTOR - %
AVG. OF CONSUMERS' MONTHLY LOAD FACTORS - %

Figure 3. Empirical trend in the relation between coincidence factor and load factor

Based on one-half-hour integrated demands in December for groups of 30 consumers

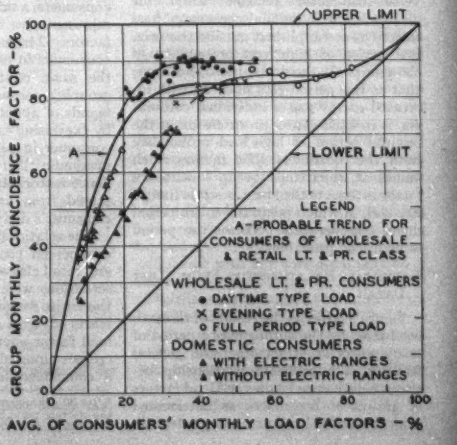
UPPER LIMIT
A
LOWER LIMIT
LEGEND
A-PROBABLE TREND FOR CONSUMERS OF WHOLESALE & RETAIL LT. & PR. CLASS
WHOLESALE LT. & PR. CONSUMERS
● DAYTIME TYPE LOAD
× EVENING TYPE LOAD
○ FULL PERIOD TYPE LOAD
DOMESTIC CONSUMERS
▲ WITH ELECTRIC RANGES
▲ WITHOUT ELECTRIC RANGES
GROUP MONTHLY COINCIDENCE FACTOR - %
AVG. OF CONSUMERS' MONTHLY LOAD FACTORS - %

Figure 5. Comparison of empirical trends in the relations between coincidence factors and load factors of different classes of consumers

Based on one-half-hour integrated demands in December for groups of 30 consumers reflecting 1936 test data for the wholesale light and power consumers and 1939 test data for domestic consumers

load factors. *The existence of the probable relationships can be obtained only from a large number of test observations of the actual behavior of loads of different classes of consumers.*

At this point it may be well to pause to consider the theoretical significance of certain lines and slopes depicted in Figure 2. It may be demonstrated that any straight line, such as *AE*, from the origin upward and above the lower limit line *AB*, represents the path of the coincidence-factor-versus-load-factor relationship for the theoretical conditions when the predominant and, therefore, the maximum use of service for a large group of consumers is confined to a certain portion of the entire period under consideration, and when all the changes in the consumers' load factors are accomplished through changes in energy use in that period. Hereinafter it will be referred to as the period of high load probability. The shorter this period, the steeper the slope of the straight line, so that, for example, line *AC* represents the shortest period or the full coincidence of maximum demands of all consumers in a group. Line *AB*, however, depicting the lower limit of the relationship or, as it may be called, the "best possible line," represents the longest period of high load probability as it applies to conditions when the loads of all consumers have the same probability of occurring throughout the entire period under consideration. The measure of the length of this period of high load probability in relation to the total period under consideration is obtained by projecting upon the abscissa the point of intersection of such a line as *AE* with the upper limit of the possible relationship indicated by line *CB*.

A horizontal line such as *FG* drawn from the ordinate or from any line such as *AE* toward the "best possible line" will be the path of the coincidence-factor-versus-load-factor relation when the change in the individual consumers' load factors is accomplished outside the original period of high load probability of the group. It should be noted, however, that as this period gets filled up with increased energy use of individual consumers, it in itself causes an extension of the original period of high-load probability until the consumers' load factors reach values at which their group coincidence factor intersects the "best possible limit," line *AB*, at which point the entire period under consideration becomes the period of high load probability.

Empirical Relationship From Test Data

Figure 3 presents the results of research conducted by the author over a period of many years in establishing the general features of a probable relationship between coincidence factors and load factors of groups of consumers as determined from the service loads of one large electric-utility system operating in metropolitan, suburban, and rural territories in the eastern part of the United States.

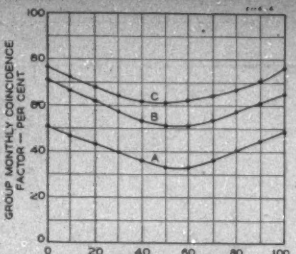

Figure 6. Illustration of effects of different mixtures of load types, for groups of 30 consumers, upon group coincidence factors of the retail light and power class reflecting 1938 test data

A—Consumers with 10-per-cent monthly load factors

B—Consumers with 20-per-cent monthly load factors

C—Consumers with 30-per-cent monthly load factors

The test observations were obtained generally for the month of December over a period of several years from integrated half-hourly load records and from a large number of consumers of several classes of the general service. They include test data for almost a decade before World War II, data during the defense period of this country and, finally, data at the height of this country's war-production activities. The procedure of analysis was uniform throughout. Consumers studied were arranged into groups, each falling into specified rather narrow load-factor limits. Each group consisted of 30 consumers, a sufficient number to produce representative results of the coincidence factors. The maximum load values of all consumers in each group were placed on the same relative-size basis either by grouping consumers with maximum demands of about the same magnitude, or by expressing each half-hour demand of a consumer in per cent of the consumer's maximum half-hour demand. Coincidence factors shown in Figure 3 were obtained from an analysis of individual consumer's daily load curves.

The relationship for the industrial and commercial consumers of the wholesale and retail classes of service, for which observations were available for practically the entire range of monthly load factors, starts out from a value close to zero* at a load factor approaching zero, rapidly increases along almost a straight line to a coincidence-factor value of about 75 per cent at 20-per-cent load factor, thereafter bends sharply to the right and rises slowly to 84 per cent at 40-per-cent load factor and then remains substantially fixed at that level of coincidence factor until reaching a load factor in excess of 70 per cent beyond which it turns up sharply and approaches the "best possible line" in the ultrahigh load-factor range.

Thus, from the foregoing theoretical considerations, the broad generalized behavior of the coincidence-factor-versus-load-factor relationship in practice appears to follow three distinct phases, although, as may be expected, the conditions obtained toward the end of the first phase merge with the conditions obtained at the beginning of the second phase, and the conditions obtained at the end of the second phase merge with the conditions obtained at the beginning of the third phase.

Phase one, obtained in the low-load-factor range, appears to indicate that, for a given classification of consumers, the high probability for the occurrence of the consumer's predominant energy use is confined to a certain well-defined portion of the entire period under consideration, and the predominant changes in the individual-consumer's-load factors are accomplished through changes in the extent of energy use almost entirely in that period.** Thus, in this load-factor region, the coincidence factor rises rapidly and almost in direct proportion to the rise in individual-consumer's-load factors. This phase of coincidence-factor-versus-load-factor behavior approximates that depicted by the theoretical line *AE* in Figure 2. Projecting upwards the portion of the empirical line which approaches a straight line from zero, we find it intersects the upper limit of the possible relationship at a point which corresponds to an individual consumer's monthly load factor of about 22 per cent, indicating that the length of the period of high-load probability is 22 per cent of the total period under consideration. Since the entire period is the month of December, the length of the high load probability thus becomes about 164 hours, or slightly more than four weeks of 40 working hours each.

Phase two, obtained in the medium-load-factor range appears to indicate that beyond individual consumers' monthly load factors of 30 per cent, a further improvement in their load factors is accomplished almost entirely *outside* the period of the group's original high load probability. Thus in this load-factor range the coincidence factor remains substantially fixed, and its behavior with

* For 30 consumers in a group used in this study, the starting point at load factor approaching zero is actually 1÷30=0.0333.

** Actually, minor changes must be occurring outside of this period because the empirical relationship as determined by test observations in the low-load-factor range is not strictly a straight line, but is a curve sloping toward the lower limit of the possible relationship, thus indicating the presence of a small horizontal component, in addition to a major upward one.

respect to load factor approximates that depicted by the theoretical line *FG* in Figure 2. This phase of the relationship was of utmost significance in appraising the combined load requirements of industrial consumers during this war as a result of substantial changes in the industrial-consumers' load factors through the addition of the second and third shifts and through the extension of the working periods into Saturdays, Sundays, and holidays. Actual experience through this war period, and as indicated by the test points in Figure 3, substantiate the fundamental nature of the empirical relationship developed from actual test observations before the war.

Phase three, obtained in the ultrahigh-load-factor range, appears to indicate that beyond an 80-per-cent monthly load factor the entire period under consideration becomes the period of high load probability for the occurrence of the consumers' predominant use of service so that further improvement in consumers' load factors are accomplished at random throughout this entire period. Thus in this ultrahigh-load-factor region the coincidence-factor-versus-load-factor relationship approaches the lower limit of the possible relationship or what may be called the "best possible line."

Present indications point to the fact that this general relationship is basic and fundamental over the entire range of load-factor values, but the numerical values obtained in practice will be different, not only for different classes of consumers, or different appliances and applications, but also for the same types of consumers and appliances in different communities.

The slope of the line in the low-load-factor range depends upon the relationship between the length of period of high load probability of the classification to the total length of the entire period under consideration. That relationship is determined largely by factors mentioned at the beginning of the paper such as population habits, community and business practices, weather and other climatic conditions, and, in addition, also depends upon the relative composition of the types of load represented by a given classification.

Based on the foregoing discussion it is now possible to formulate qualitatively the coincidence-factor-versus-load-factor relationship as follows:

For a large number of consumers, of equal size, with no artificial restrictions placed in the way of their service use, and with all other things equal, the degree of coincidence of the maximum power requirements of individual consumers in a group changes with the change in their individual load factors. In the low-load-factor range the coincidence factor increases rapidly with the increase in the individual consumers' load factors. Its rate of change is substantially constant and is inversely proportional to the relative length of the high load probability of the class. In the medium range of load factors the magnitude of the group coincidence factor remains substantially fixed, until very high-load-factor values are reached, when the relation between load factor and coincidence factor approaches the lower limit of the possible relationship.

Care should be exercised in the interpretation and the use of this relationship and the following qualifications must be borne in mind:

1. It is an empirical relation and is based on the conditions and experience of one utility system supplying a given community. Other communities with different population habits, different definition as to what constitutes a class of service, different weather and other climatic conditions, may differ in the actual magnitudes of the coincidence factors shown throughout the entire load-factor range.

2. The relation is confined to consumers of substantially the same size, taking the same class of service, operating at the same load factors, and always taken in sufficient numbers for each type, size, and load factor to produce representative results on a coincidence factor of the group. It is obvious that, unless these qualifications are observed fully, different coincidence factors may be obtained.

3. The coincidence factors obtained from Figure 3 are those for individual consumers within a group applied to monthly conditions. There will be additional coincidence factors between different groups of any one class of service, for longer periods than a month, and between different classes of service of a system.

It should be noted also that the foregoing empirical relationship depicted the coincidence factors which, when applied to the consumers' individual maximum monthly demands, would, by definition, produce the coincident maximum demand of the group without indicating its time occurrence. Additional information is required for translating these coincident maximum group demands to load values for different hours of the day or for different days of the month. Such information can be secured only through extensive study of load-curve shapes of individual groups or classes of consumers.

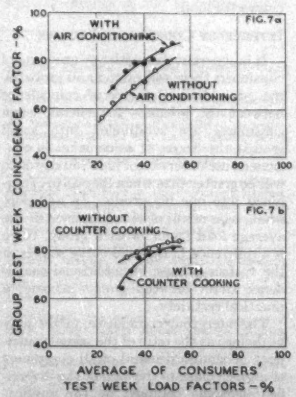

Figure 7. Illustration of the effect of the addition of certain appliances upon the coincidence factors of consumers of the commercial class reflecting 1940–1941 test data

Effect of Number of Consumers on the Coincidence-Factor-Versus-Load-Factor Relationship

The results of practical observations reflected in Figure 3 are based upon 30 consumers in a group. Obviously, for one single consumer in a group, by definition the coincidence factor is unity no matter what the load factors, and for an infinite number of consumers, from Figure 1, the coincidence factor may be expected to be lower than for groups of 30 consumers, throughout the entire load-factor range.

Referring to Figure 1, it is possible to construct a set of curves depicting the coincidence-factor-versus-load-factor relationships for various numbers of consumers in a group ranging from one to infinity. These relationships are shown in Figure 4, employing the equation of Figure 1 and the coincidence-factor-versus-load-factor relationship of the commercial and industrial classification shown in Figure 3. It should be noted that these relationships too, insofar as numerical values are concerned, are subject to the same qualifications as the relationship depicted in Figure 3.

The Influence of Different Classes of Consumers, or of Consumers With Different Types of Loads, Upon the Coincidence-Factor-Versus-Load-Factor Relationship

Figure 5 shows the coincidence-factor-versus-load-factor relationship for domestic consumers without electric ranges, and for domestic consumers with electric ranges, in comparison with the relationship for consumers of the commercial and industrial classification shown in Figure 3.

It will be noted that the relationships for the domestic consumers follow the general trend of the commercial and industrial consumers in the lower-load-factor range, although at a lower level. No test observations were available for these classes of consumers in the medium- and high-load-factor ranges, although it is believed that the extended relationship beyond the available test observations will merge with the horizontal portion of the relationship for the commercial and industrial consumers and thereafter follow it to the lower limiting value. The slope of the relationship for the domestic-service class without ranges is lower than that for the commercial-industrial classification. This would indicate that the period of high load probability for the domestic consumers is relatively longer

than for the commercial and industrial ones, since the use period of domestic consumers without electric ranges can extend easily to twice the number of hours per week than that of consumers of the commercial and industrial classes whose individual load factors correspond to those of the domestic consumers, especially since Saturdays, Sundays, and holidays are days of fairly high domestic activity insofar as the use of electric service is concerned. For some of the appliances, the electric refrigerator for example, the entire period under consideration becomes the period of high load probability. However, the difference in the coincidence factors of the domestic and commercial classes of service practically disappears with the introduction of the electric range load in the domestic class because the period of high load probability of the range, with its predominant load requirements, is confined to much shorter periods during the day.

Figure 5 also shows the individual coincidence-factor-versus-load-factor relationship for three major types of consumers in the wholesale light and power classification, in comparison with the general relationship for the commercial and industrial consumers. For purpose of this comparison a classification depending upon the period of maximum average use of energy was employed. The daytime-type consumes was defined as one having maximum average use between 9 a.m. and 4 p.m.; the evening type as having the maximum average use between 4 p.m. and 9 p.m.; and the full-time type as having about an equal use in each of these periods with a resulting high load factor. This classification of load types caused the industrial consumers to fall principally into the daytime and full-time groups, whereas the commercial consumers fell principally into the evening group.

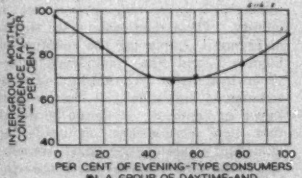

Figure 8. Illustration of the effect of different mixtures of load types upon the intergroup coincidence factor of the retail light and power class reflecting 1938 test data

It will be noted that the coincidence-factor-versus-load-factor relationships for individual types of consumer loads of a given classification follow the general trends of the formulated relationship, but the numerical values of the coincidence factors of the individual types are generally higher than those of the entire class.

Figure 6 illustrates the effect on group coincidence factors of a different mixture of load types for given consumers' load factors. The curves on this chart show the variation in group coincidence factors of a mixed group of thirty consumers with variation in the degree of mixture of daytime and evening load types, averaging 10-per-cent, 20-per-cent and 30-per-cent load factors. They bring out the fact that higher coincidence factors are obtained for groups of consumers homogeneous as to load type than for heterogeneous groups, and the greatest deviation between homogeneous and non-homogeneous groups is found at the lower load factors.

Figure 7 shows the coincidence-factor-versus-load-factor relationships for two special types of commercial consumers. From Figure 7a it will be observed that the coincidence-factor-versus-load-factor relationship for commercial consumers *with* air conditioning is higher than for the same consumers *without* air conditioning. The difference is substantial in the range of consumers' load factors commonly encountered in practice (between 20 per cent and 40 per cent).

From Figure 7b it will be observed that the coincidence-factor-versus-load-factor relationship for commercial consumers *with* electric counter cooking equipment is lower than for the same consumers *without* the counter cooking equipment, indicating the beneficial effects of this load upon consumers' load characteristics. It should be noted, however, that one of the reasons for this is due to the fact that, for the consumers tested, the relative size of the connected electric counter cooking load did not exceed three times their other connected load.

Intergroup Coincidence Factors

It is apparent that with any grouping of consumers there will exist, in all probability, an additional factor of coincidence between the groups. In general, when consumers are subdivided into small groups, the degree of coincidence in consumers' use of service of individual groups will be greater than when they all are combined into one big group. In addition, when, as a result of the difference in the average load factor of each group, there is a difference in the load-curve shapes of the various groups, an additional coincidence factor between groups becomes a practical certainty.

The intergroup coincidence factor may be defined as the ratio of the actual coincident maximum demand of all consumers of a given class to the sum of the diversified demands obtained by the application of the coincidence-factor-versus-load-factor relationship to the individual consumers' load characteristics.

The intergroup coincidence factors for consumers homogeneous as to load type may be expected to be higher than for the entire group of consumers of diverse types of load. Figure 8 illustrates the trend in the intergroup coincidence factors for various combinations of daytime- and evening-loading-type consumers, bringing out the point that higher intergroup coincidence factors will be obtained for groups with highly homogeneous-type loads, than for groups with comparatively high heterogeneous load types.

From the indicated curves of Figures 3, 4, and 5, and actual test-load-curve data, the intergroup coincidence factors were found to vary from between 93 per cent and 100 per cent for the commercial and industrial classes of consumers, and from 92 per cent to 95 per cent for consumers of the domestic classification with and without electric ranges.

Conclusion

From the foregoing discussion, it is possible to make the following significant observations:

1. The degree of coincidence in the use of electric service depends upon many factors. Among the more important ones are population habits, community and business practices, weather and other climatic conditions, design of utilization equipment, and methods used in the control of service.

2. Numerical values of coincidence factors will differ for different load applications, different classes of consumers, and different composition of load types in a given classification. They can be obtained with any degree of certainty only from actual test observations, and must be checked periodically to detect the effects of changing conditions. In view of the complexity of forces influencing group load characteristics, it is obvious that no single mathematical formula with a given set of constants can be right for all conditions. Mathematical considerations can serve only as a means for rationalizing the results of practical observations.

3. In general, the degree of coincidence in the maximum requirements of electric service of a group of consumers homogeneous as to some controlling characteristic decreases along a path resembling that of a rectangular hyperbola from a value of unity for one consumer in a group to values approaching the horizontal asymptote of the rectangular hyperbola for an infinite number of consumers in a group. The convergence of the relationship toward this asymptote is comparatively rapid for all asymptotic values of coincidence factors, and is more rapid for the higher values than for the lower ones.

Statistically stable results in coincidence factors may be expected in the practical range of load factors for as few as 100 consumers in a group and results of sufficient engineering stability even can be obtained from groups of 30 to 50 consumers.

4. In general, the degree of coincidence in the maximum requirements of electric service of groups of consumers changes with the change in their individual load factors.

Synchronous Starting of Generator and Motor

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ASSOCIATE AIEE

ASYNCHRONOUS motor, generator, or condenser can be started from rest, by means of shaft torque, induction-motor (amortisseur winding) torque, or synchronizing torque. This paper presents data on the last method of starting. The system studied consists of a prime mover driving a synchronous generator, and a synchronous machine driven electrically by the generator. The whole system is started from rest by means of torque applied to the generator shaft, the motor being accelerated to normal speed by the synchronous torque developed. The performance of such a system was determined both by tests on several machines and by calculations with the aid of the differential analyzer at the University of Pennsylvania, and limiting conditions and criteria for successful starting were found in terms of the various pertinent system parameters. In a few cases a system consisting of a generator and two motors was studied.

Synchronous motors and condensers ordinarily are started by means of the induction-motor torque developed by their amortisseur windings. In some cases, however, for example when a generator is used as a condenser, it becomes necessary to start the machine in some other way. A salient-pole generator may have no amortisseur winding or one of insufficient torque and thermal capacity. A turbine generator will, in general, develop a large starting torque but will have insufficient thermal capacity. In many such cases the machine has been started by electrically connecting the motor and generator with both machines at rest and excited, then starting the generator by applied turbine torque and pulling up the motor by the synchronous torque developed at very low speeds. This method has been used for many years in the field testing of water-wheel generators and in miscellaneous shop tests. In case of extremely large motors with high starting torques, it may be convenient to arrange the electric-system connections so that a generator may be assigned the job of starting the motor on its synchronizing torque, thus permitting a reduction in the required capacity of the amortisseur winding.

The conditions required for successful starting in this manner have been studied in an approximate way by several investigators[1,2] and certain rules have been developed. However, it is believed that the problem is sufficiently complex and of sufficient general interest to justify the presentation of a more exact treatment, particularly since this more exact treatment has been found necessary to predict starting performance correctly in the range studied.

The problem is very similar to that of synchronizing or pulling-into-step of synchronous motors at normal speed[3,4] except that now the performance of two or three machines must be considered simultaneously, and the speed range is relatively very much greater.

Conclusions

From the results of the tests and calculations discussed in this paper, the following conclusions can be drawn regarding starting performance in the range covered:

1. The optimum ratio of motor excitation to generator excitation is such that the ratio of the normal speed, open circuit voltages is about 0.8. That is, at this ratio the maximum motor friction torque can be started (Figure 1). In general, the generator

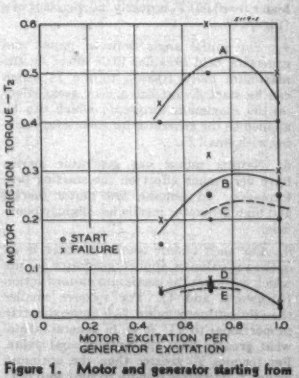

Figure 1. Motor and generator starting from standstill with applied generator shaft torque

Maximum motor friction torque T_3 which can be started, as function of excitation ratio E_2/E_1.
$H_3 = 2.53$, $E_1 = 1.3$

Curve	r	x	H_1
A	0.01	1.0	5.05
B	0.025	1.0	5.05
C	0.025	1.0	1.96
D	0.05	1.0	5.05
E	0.05	0.5	5.05

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in the low load-factor range the coincidence factor increases rapidly with the increase in the individual consumers' load factors. In the medium range of load factors its magnitude remains substantially fixed at a level of around 84 per cent until very high load-factor values are reached when it approaches the lower limit of the possible relationship.

5. The general level in the degree of coincidence in the maximum requirements of electric service are higher for groups of consumers homogeneous as to load type than for heterogeneous groups, and large deviations between homogeneous and non-homogeneous groups are found at the lower load factors than at the higher ones.

6. Intergroup coincidence factors for homogeneous-type loads may be expected to be higher than those for diverse types of load.

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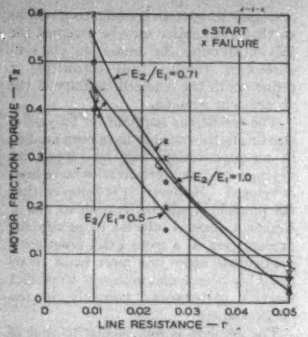


Figure 2. Motor and generator starting from standstill with applied generator shaft torque

Maximum motor friction torque T_2 which can be started, as function of circuit resistance r. $H_1=5.05$, $H_2=2.53$, $x=1.0$

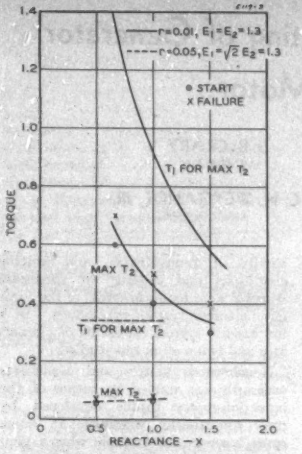


Figure 3. Motor and generator starting from standstill with applied generator shaft torque

Maximum motor friction torque T_2 which can be started, as function of circuit reactance X. $H_1=5.0$, $H_2=2.55$

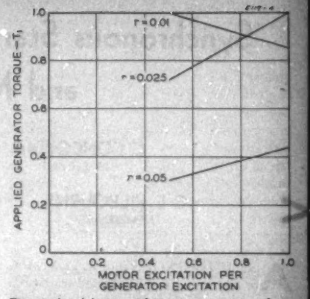


Figure 4. Motor and generator starting from standstill

Required generator shaft torque T_1 to obtain maximum motor friction torque T_2, as function of excitation ratio E_2/E_1

$H_1=5.05$, $H_2=2.53$, $x=1.0$, $E_1=1.3$

ator excitation should be as great as possible.

2. Considerable motor torque can be developed by synchronous starting when the total armature-circuit resistance is low, but high resistance reduces the maximum allowable motor friction torque (T_2) very much. With line resistances greater than five per cent, T_2 becomes less than seven per cent (Figure 2).

3. With small line resistance r ($r=0.01$) the maximum motor friction torque T_2 which can be started is practically inversely proportional to line reactance x, while with high r ($r=0.05$) T_2 is nearly independent of x (Figure 3).

4. The initial angle between motor and generator field axes has little effect on the maximum motor friction torque T_2 which can be started, but has a very great effect on the maximum torque T_1 which can be applied to the generator for successful starting with small T_2.

5. Neither motor nor generator inertia have very much effect on the starting performance. In general, low motor inertia and high generator inertia are slightly beneficial.

6. For each circuit condition there is an optimum value of applied generator torque which will start the maximum motor friction (Figures 3 and 4). For torques smaller than the optimum value, T_2 is approximately proportional to T_1; it is, in general, somewhat greater than the proportional value. For torques T_1 greater than the optimum value, T_2 decreases rapidly to zero, and if T_1 is too large the generator will run away leaving the motor oscillating about zero speed.

7. It is desirable to have a fairly low-resistance amortisseur winding on both motor and generator if they are not of solid-pole-face construction.

8. When motor and generator are directly connected electrically, turbomachines should, in general, be easier to start than salient-pole machines.

Analysis

The systems considered are shown in Figure 5. In order to reduce the performance equations of these systems to practically soluble forms, it was assumed that:

1. All machines have symmetric rotors.

2. The effective machine excitations and reactances are constant during the starting period. This may be interpreted as meaning that the rotor flux is constant or that some average value is taken as representative.

3. Amortisseur effects are negligible.

The system equations for the case of two machines, in an integral form suitable for solution on the differential analyzer, are then (see appendix)

$$\left.\begin{aligned} xi_\alpha &= +E_1\cos\theta_1 - E_2\cos\theta_2 - \int ri_\alpha dt \\ xi_\beta &= +E_1\sin\theta_1 - E_2\sin\theta_2 - \int ri_\beta dt \\ M_1 p\theta_1 &= -E_1\int \cos\theta_1 d\int i_\beta dt + E_1\times \\ &\quad \int \sin\theta_1 d\int i_\alpha dt - \int T_1 dt \\ M_2 p\theta_2 &= +E_2\int \cos\theta_2 d\int i_\beta dt - E_2\times \\ &\quad \int \sin\theta_2 d\int i_\alpha dt - \int T_2 dt \end{aligned}\right\} \quad (1)$$

where

t = per-unit time
x = per-unit armature-circuit reactance
r = per-unit armature-circuit resistance
E = per-unit excitation
θ = rotor angle
M = per-unit rotor inertia
$M=4\pi fH$, where H is the inertia constant as conventionally defined in stability studies

$$H=\frac{0.231\times WR^2\times(\text{rpm})^2}{10^6 \text{ kva (base)}}$$

f = rated circuit frequency in cycles per second ($f=60$ in all numerical examples)
i_α, i_β = per-unit equivalent two-phase armature currents of machine one
T = per-unit load torque

Subscripts 1 and 2 refer to generator and motor, respectively. A schematic diagram of the required analyzer connections is shown in Figure 6.

With the motor (machine two) at standstill θ_2 is constant and the performance is determined by the first three parts of equation 1. The motor torque is

$$\text{torque}=i_\beta E_2\cos\theta_2 - i_\alpha E_2\sin\theta_2 \quad (2)$$

so the motor may be started (that is, the fourth equation may be connected in the circuit) when its torque becomes equal to the friction torque selected.

The procedure followed on the differential analyzer was as follows. For each value of resistance, reactance, motor inertia, generator inertia, motor excitation, generator excitation, and applied generator torque, the motions of the two machines were determined up to a point where it was decided that the motor could or could not be started successfully. This was done for several values of motor friction and initial motor–generator angle until the maximum friction torque which could be started at any angle was found. Occasionally this procedure was varied in detail by finding the limiting generator torque for a given motor torque. Figure 7 shows a typical limiting curve and illustrates the fact that the allowable motor friction torque increases to a maximum and then decreases to zero as the applied (constant) generator torque is increased.

In most of the work done, the motor

friction torque was maintained at its static breakaway value throughout the starting period. The friction torque actually will decrease somewhat, but, for generators with large numbers of poles, the total mechanical angle through which the motor has turned by the time it either definitely has pulled in or failed to pull in is very small, since the total electrical angle is only two or three revolutions. For machines with two or four poles the results may be somewhat pessimistic in the sense that the calculations may indicate a failure to start when a start actually might be accomplished. An investigation of this point in a particular case showed about a 40-per-cent increase in the allowable motor static friction, if it were dropped to zero at the instant of motor starting.

The generator excitation E_1 was 1.3 in nearly all cases. This was considered to correspond to about the highest value of field flux which could be maintained in a normal machine without exceeding the capacity of the field winding. The motor excitation E_2 was varied from 1.3 down to 0.65 since one of the principal objects of the study was to determine the optimum excitation ratio as a function of the other system parameters. In order to interpret the results in terms of other generator excitations, and, in general, to obtain the maximum amount of information from the results, one may note that the system behavior may be expressed in terms of the six groups:

$$\frac{xM_1}{E_1^2},\ \frac{xM_2}{E_1^2},\ \frac{xT_1}{E_1^2},\ \frac{xT_2}{E_1^2},\ \frac{r}{x},\ \frac{E_2}{E_1}$$

The attempt to start was taken as successful if the motor speed exceeded the generator speed at least twice. That is, in a successful start the motor usually would start up and oscillate about the generator. Since all rotor damping was neglected it sometimes was observed that these oscillations tended to increase in magnitude. A calculation for the condition of small oscillations about a constant average speed shows that in the speed range considered the system treated here is damped negatively. At very low speeds the damping is positive, but at between one per cent and two per cent speed the damping becomes negative, reaching a negative maximum at about two per cent speed and remaining negative but becoming continually smaller in magnitude thereafter. Calculations have shown that an amortisseur winding of normal design on both motor and generator is adequate to keep the damping positive at all speeds. Moreover, even if damping is negative over a certain speed range, the machines may not drop out of step unless the period of operation in the range is sufficiently long.

Calculations were made to find the effects of line resistance and reactance, excitation ratio, motor-generator initial electrical angle, inertias of motor and generator, and applied torque on the starting characteristics, that is, on the permissible motor starting friction. The total reactance was taken as 1.0 per unit, which should correspond approximately to the total transient reactance of the usual two-machine system. This reactance was varied in a few cases between 0.5 and 1.5. The total line resistance was varied from 0.01, which could correspond to that for two machines tied directly together, to 0.05, which allows for some tie-line resistance.

Depending on the initial displacement angle, the motor starts either forward or backward and may or may not synchronize if it is a border-line case. The worst initial angle of the motor relative to the generator was usually between -90 degrees and -180 degrees. In most cases only 90-degree intervals were checked, but in a few cases 45-degree intervals were considered. The effect of angle was not sufficiently great to make it necessary to consider smaller intervals.

Test Checks

In order to check the validity of the simplified equations used to represent the system, several tests were made. A 9,000-horsepower 18-pole vertical synchronous motor having a static friction of 17 per cent was started from a 20-pole horizontal machine of about equal size. The prime mover was a d-c motor and the system was started by closing the motor

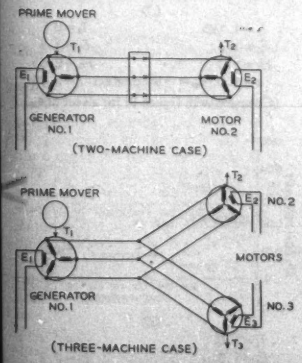


Figure 5. Motor and generator starting from standstill with applied generator shaft torque

System diagrams

Figure 6. Motor and generator starting from standstill with applied generator shaft torque

Differential-analyzer connection diagram

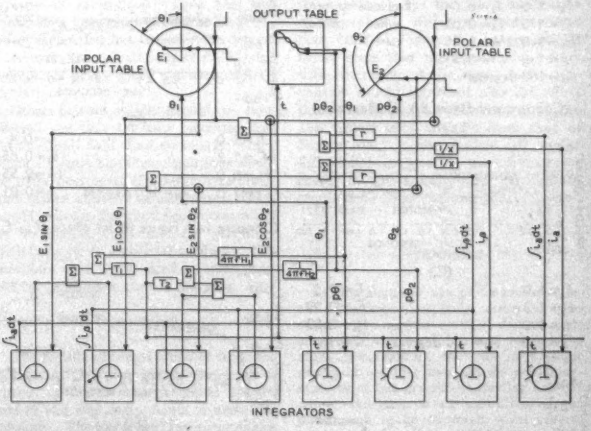
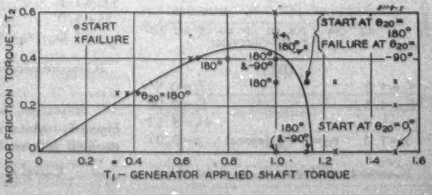
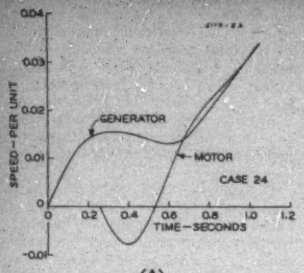


Figure 7. Motor and generator starting from standstill with applied generator shaft torque

Motor friction torque T_2, which can be started, as function of generator applied torque T_1

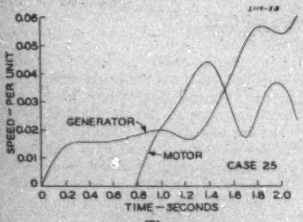
$H_1 = 5.0$, $H_2 = 2.55$, $r = 0.01$, $x = 1.0$, $E_1 = E_2 = 1.3$





(A)

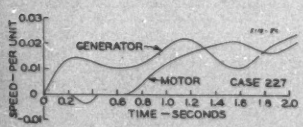
$T_1=1.0$ $T_2=0.41$ (Reduced to zero when motor starts)
$E_1=1.3$ $E_2=0.65$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $r=0.015$
$\theta_m=180$ degrees



(B)

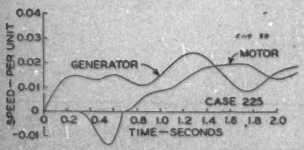
$T_1=1.0$ $T_2=0.648$ (Reduced to zero when motor starts)
$E_1=1.3$ $E_2=0.65$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $r=0.015$
$\theta_m=180$ degrees

(Compare with Figure 8A for effect of T_2)



(C)

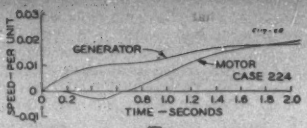
$T_1=1.0$ $T_2=0.5$
$E_1=1.3$ $E_2=0.92$
$H_1=5.0$ $H_2=2.53$
$x=1.0$ $\theta_m=180$ degrees $r=0.01$



(D)

$T_1=1.0$ $T_2=0.5$
$E_1=1.3$ $E_2=0.92$
$H_1=5.0$ $H_2=2.53$
$x=1.0$ $\theta_m=-90$ degrees $r=0.01$

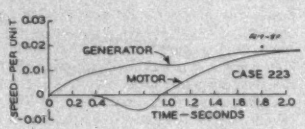
(Compare with Figure 8C for effect of θ_m)



(E)

$T_1=0.375$ $T_2=0.0667$
$E_1=1.3$ $E_2=0.92$
$H_1=5.0$ $H_2=2.53$
$x=1.0$ $\theta_m=180$ degrees $r=0.05$

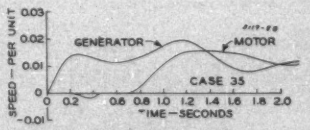
(Compare with Figure 8C for effect of r, and with Figure 8F for effect of θ_m)



(F)

$T_1=0.375$ $T_2=0.0667$
$E_1=1.3$ $E_2=0.92$
$H_1=5.0$ $H_2=2.53$
$x=1.0$ $\theta_m=-90$ degrees $r=0.05$

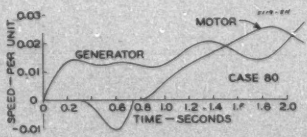
(Compare with Figure 8E for effect of θ_m, and with Figure 8D for effect of r)



(G)

$T_1=1.0$ $T_2=0.4$
$E_1=1.3$ $E_2=0.65$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $\theta_m=180$ degrees $r=0.01$

(Compare with Figure 8K for effect of E_2/E_1)



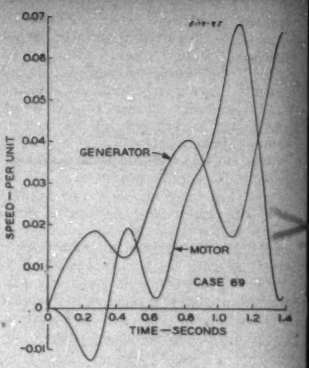
(H)

$T_1=1.0$ $T_2=0.4$
$E_1=1.3$ $E_2=0.65$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $\theta_m=-90$ degrees $r=0.01$

(Compare with Figure 8G for effect of θ_m)

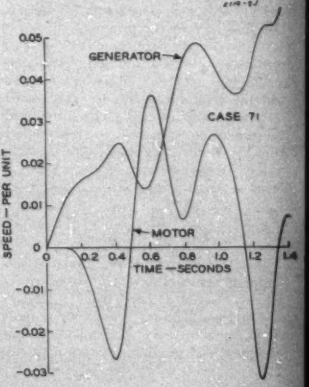
Figure 8. Motor and generator starting from standstill with applied generator shaft torque

Curves of speed versus time



(I)

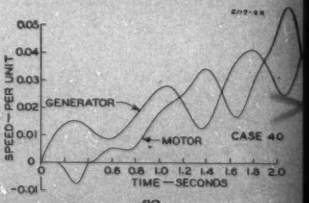
$T_1=1.125$ $T_2=0$
$E_1=1.3$ $E_2=1.3$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $\theta_m=180$ degrees $r=0.01$



(J)

$T_1=1.125$ $T_2=0$
$E_1=1.3$ $E_2=1.3$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $\theta_m=-90$ degrees $r=0.01$

(Compare with Figure 8I for effect of θ_m)



(K)

$T_1=1.0$ $T_2=0.4$
$E_1=1.3$ $E_2=1.3$
$H_1=5.0$ $H_2=2.55$
$x=1.0$ $\theta_m=180$ degrees $r=0.01$

(Compare with Figure 8G for effect of E_2/E_1)

armature switch with field already applied. The torque thus was built up very rapidly and decayed slowly as the d-c motor accelerated. With excitation ratios of from 0.5 to 1.0 the lowest generator excitation (about 65 per cent) at which the a-c motor could be started was found.

The critical excitations for this system then were calculated on the differential analyzer and checked very closely. (See Table I.) There were, however, some differences between the test and analyzer conditions which are enumerated in the following.

In the calculation the motor friction torque was reduced to zero as soon as the motor started, while the friction of the test motor may be presumed to require some little time to fall to a completely negligible value. This indicates that the calculation may be really pessimistic since the consideration of an additional motor friction would have increased the critical excitations obtained. An increase of about five to ten per cent in excitation would be expected.

On the other hand, an armature resistance of $r=0.015$ was used in some of the calculations, while the test d-c resistance was closer to $r=0.01$. This indicates a somewhat optimistic calculation. The resultant decrease in critical excitation is shown by Figure 2 to be not more than about five per cent (torque varies as the square of excitation). Thus the two differences between calculation and test offset each other to a considerable degree. Moreover, the calculations at $E_2/E_1=0.5$ were made with $r=0.01$ and showed little deviation.

Other factors which should be considered are that the test machines had rather small field time constants, which would indicate that the calculations would be more pessimistic for larger machines, and rather effective amortisseurs, which would indicate that the calculations might be somewhat optimistic for machines with little or no amortisseur effect. The machines were represented by their transient reactances in the calculations.

Results and Discussion

The results obtained directly from the differential analyzer are in the form of curves of motor and generator speeds, and of the two components of armature current. The motor and generator angles also were determined in most cases. Figure 8 shows a few typical curves of motor and generator speed.

The information taken from these curves is summarized in Figures 1–4. Figure 1 shows the effect of excitation ratio and of line resistance. It is seen that regardless of line resistance the optimum excitation ratio is about 0.8, and that for the highest resistance ($r=0.05$) the permissible motor friction at a ratio of 1.0 is relatively much lower. For this high-resistance case an optimum ratio of 0.7 might apply, since it is possible to draw the curve in several ways through the check points.

Figure 2 is a replot of some of the curves of Figure 1 to show the effect of line resistance more directly. This curve brings out very clearly the importance of a low tie-line resistance if this method of starting is to be used on a motor having any very large breakaway torque, and also shows that if the tie resistance is kept down considerable torque may be developed.

Figures 3 and 4 show the generator torque T_1 which should be applied in order to start the maximum possible motor torque. These T_1 curves are only approximate, as the optimum value of T_1 is not very critical (see Figure 7). From Figure 7 it is seen that the optimum T_1 should not be greatly exceeded. Each point of the summary curves (Figures 1–4) was determined from curves similar to Figure 7, and each point of Figure 7 was, in turn, determined from curves similar to those of Figure 8.

Figure 9 shows the results of a calculation for the case of one generator starting two motors simultaneously, each of half the generator rating. One motor is at an initial angle of 90 degrees, the other at 180 degrees. If both motors are initially at 180 degrees, they may be considered as one. The starting performance is then the same as that of the two-machine case of Figure 10A, which is slightly worse than that of Figure 9. In general, it would seem that the two-machine case, with the motor at the worst angle, adequately should represent also the worst three-machine case. The case of Figure 10B differs only slightly from that of Figure 10A. It was worked out on the differential analyzer as an approximate check of the step-by-step calculations required for Figures 9 and 10A.

Appendix

In this appendix the performance equations for three electrically connected symmetric rotor machines will be derived first, since they may be of interest, not only to study, for example, the case of a single generator starting two motors simultaneously or of two generators starting a single motor, but also as an indication of the phenomena to be expected when several machines are so connected together. The equations for two machines studied in detail in this paper then will be derived as a special case.

Table I

E_2/E_1	E_1 (Calculated)	E_1 (Test)
0.5	0.65	0.64
0.67	0.64	0.63
1.0	0.60	0.58

The voltage equations for machine one are[4]

$$\left.\begin{aligned} e_{\alpha 1} &= p\psi_{\alpha 1} - r_1 i_{\alpha 1} \\ e_{\beta 1} &= p\psi_{\beta 1} - r_1 i_{\beta 1} \end{aligned}\right\} \quad (3)$$

Under the assumptions, the flux linkages are[4]

$$\left.\begin{aligned} \psi_{d1} &= E_1 - x_1 i_{d1} \\ \psi_{q1} &= -x_1 i_{q1} \end{aligned}\right\} \quad (4)$$

The d-, q-axis quantities are related to the α-, β-axis quantities by the relations[4]

$$\left.\begin{aligned} i_d &= i_\alpha \cos\theta + i_\beta \sin\theta \\ i_q &= -i_\alpha \sin\theta + i_\beta \cos\theta \end{aligned}\right\} \quad (5)$$

with similar relations for ψ and e. Substituting equations 5 in equations 4, yields

$$\left.\begin{aligned} \psi_{\alpha 1} &= E_1 \cos\theta_1 - x_1 i_{\alpha 1} \\ \psi_{\beta 1} &= E_1 \sin\theta_1 - x_1 i_{\beta 1} \end{aligned}\right\} \quad (6)$$

Now by substituting equation 6 in equation 3, the voltage equations become

$$\left.\begin{aligned} e_{\alpha 1} &= E_1 p\cos\theta_1 - (px_1 + r_1) i_{\alpha 1} \\ e_{\beta 1} &= E_1 p\sin\theta_1 - (px_1 + r_1) i_{\beta 1} \end{aligned}\right\} \quad (7)$$

Similarly, for machines two and three

$$\left.\begin{aligned} e_{\alpha 2} &= E_2 p\cos\theta_2 - (px_2 + r_2) i_{\alpha 2} \\ e_{\beta 2} &= E_2 p\sin\theta_2 - (px_2 + r_2) i_{\beta 2} \end{aligned}\right\} \quad (8)$$

$$\left.\begin{aligned} e_{\alpha 3} &= E_3 p\cos\theta_3 - (px_3 + r_3) i_{\alpha 3} \\ e_{\beta 3} &= E_3 p\sin\theta_3 - (px_3 + r_3) i_{\beta 3} \end{aligned}\right\} \quad (9)$$

To connect the three machines together, one puts

$$\left.\begin{aligned} e_{\alpha 1} &= e_{\alpha 2} = e_{\alpha 3} \\ e_{\beta 1} &= e_{\beta 2} = e_{\beta 3} \\ i_{\alpha 3} &= -i_{\alpha 1} - i_{\alpha 2} \\ i_{\beta 3} &= -i_{\beta 1} - i_{\beta 2} \end{aligned}\right\} \quad (10)$$

whence equations 7, 8, and 9 become

$$\left.\begin{aligned} (Ap^3 + Bp + C) i_{\alpha 1} &= [(x_2 + x_3)p + (r_2 + r_3)] pE_1 \cos\theta_1 - (x_3 p + r_3) \times pE_2 \cos\theta_2 - (x_2 p + r_2) pE_3 \cos\theta_3 \\ (Ap^3 + Bp + C) i_{\beta 1} &= [(x_2 + x_3)p + (r_2 + r_3)] pE_1 \sin\theta_1 - (x_3 p + r_3) \times pE_2 \sin\theta_2 - (x_2 p + r_2) pE_3 \sin\theta_3 \\ (Ap^3 + Bp + C) i_{\alpha 2} &= [(x_3 + x_1)p + (r_3 + r_1)] pE_2 \cos\theta_2 - (x_1 p + r_1) \times pE_3 \cos\theta_3 - (x_3 p + r_3) pE_1 \cos\theta_1 \\ (Ap^3 + Bp + C) i_{\beta 2} &= [(x_3 + x_1)p + (r_3 + r_1)] pE_2 \sin\theta_2 - (x_1 p + r_1) \times pE_3 \sin\theta_3 - (x_3 p + r_3) pE_1 \sin\theta_1 \end{aligned}\right\} \quad (11)$$

where

$$\left.\begin{aligned} A &= x_1 x_2 + x_2 x_3 + x_3 x_1 \\ B &= r_1(x_2 + x_3) + r_2(x_3 + x_1) + r_3(x_1 + x_2) \\ C &= r_1 r_3 + r_2 r_3 + r_3 r_1 \end{aligned}\right\} \quad (12)$$

The torque equation of each machine is of the form

$$Mp^2\theta + Ei_q + T = 0 \quad (13)$$

where T is the load torque. From equations 5 and 10, the three torque equations are

$$\left.\begin{aligned} M_1 p^2\theta_1 + E_1(i_{\beta 1}\cos\theta_1 - i_{\alpha 1}\sin\theta_1) + T_1 &= 0 \\ M_2 p^2\theta_2 + E_2(i_{\beta 2}\cos\theta_2 - i_{\alpha 2}\sin\theta_2) + T_2 &= 0 \\ M_3 p^2\theta_3 + E_3[(i_{\alpha 1} + i_{\alpha 2})\sin\theta_3 - (i_{\beta 1} + i_{\beta 2})\cos\theta_3] + T_3 &= 0 \end{aligned}\right\} \quad (14)$$

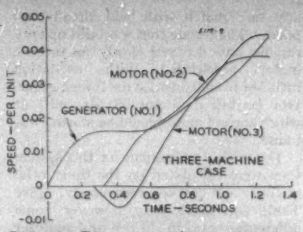


Figure 9. Two motors and generator starting from standstill with applied generator shaft torque

Speed versus time

$T_1 = 0.985$	$T_3 = T_2 = 0.20^*$
$E_1 = 1.3$	$E_2 = E_3 = 0.65$
$H_1 = 5.0$	$H_2 = H_3 = 1.65$
$x_1 = 0.5$	$x_2 = x_3 = 1.0$
$r_1 = 0.008$	$r_2 = r_3 = 0.016$

$\theta_{10} = 0$ degrees, $\theta_{20} = 90$ degrees, $\theta_{30} = 180$ degrees

*T_2 and T_3 reduced to 0.008 when motors start

(Compare with Figure 10A for effect of combining the motors)

Although equations 11 and 14 may be put directly in an integral form for solution on the differential analyzer, the number of integrations required is large. They may be simplified with little loss in generality by making the ratios of resistance to reactance the same in all three machines. If

$$\frac{r_1}{x_1} = \frac{r_2}{x_2} = \frac{r_3}{x_3} = \rho \quad (15)$$

then

$$B = 2\rho A \quad \text{and} \quad C = \rho^3 A$$

and

$$Ap^3 + Bp + C = A(p+\rho)^3$$

The current equations 11 are reduced to

$$\left.\begin{aligned} A(p+\rho) i_{\alpha 1} &= (x_2 + x_3) pE_1 \cos\theta_1 - x_3 pE_2 \cos\theta_2 - x_2 pE_3 \cos\theta_3 \\ A(p+\rho) i_{\beta 1} &= (x_2 + x_3) pE_1 \sin\theta_1 - x_3 pE_2 \sin\theta_2 - x_2 pE_3 \sin\theta_3 \\ A(p+\rho) i_{\alpha 2} &= (x_3 + x_1) pE_2 \cos\theta_2 - x_1 pE_3 \cos\theta_3 - x_3 pE_1 \cos\theta_1 \\ A(p+\rho) i_{\beta 2} &= (x_3 + x_1) pE_2 \sin\theta_2 - x_1 pE_3 \sin\theta_3 - x_3 pE_1 \sin\theta_1 \end{aligned}\right\} \quad (16)$$

Machine number three may be eliminated by letting $x_3 = \infty$, $i_{\alpha 3} = -i_{\alpha 2} = i_\alpha$, and $i_{\beta 3} = -i_{\beta 2} = i_\beta$. The first and last pair of equations 16 become identical and are represented by

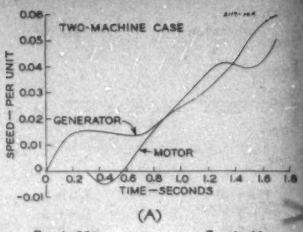
$$\left.\begin{aligned} (xp + r) i_\alpha &= p(E_1 \cos\theta_1 - E_2 \cos\theta_2) \\ (xp + r) i_\beta &= p(E_1 \sin\theta_1 - E_2 \sin\theta_2) \end{aligned}\right\} \quad (17)$$

where

$$x = x_1 + x_2 \text{ and } r = r_1 + r_2$$

The torque equations 14 become

$$\left.\begin{aligned} M_1 p^2\theta_1 + E_1(i_\beta \cos\theta_1 - i_\alpha \sin\theta_1) + T_1 &= 0 \\ M_2 p^2\theta_2 + E_2(i_\alpha \sin\theta_2 - i_\beta \cos\theta_2) + T_2 &= 0 \end{aligned}\right\} \quad (18)$$



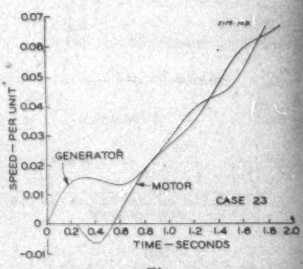
(A)

$T_1 = 0.985$	$T_2 = 0.4^*$
$E_1 = 1.3$	$E_2 = 0.65$
$H_1 = 5.0$	$H_2 = 3.3$
$x = 1.0$	$r = 0.016$

$\theta_{20} = 180$ degrees

*T_2 reduced to 0.015 when motor starts

(Compare with Figure 9 for effect of two half-size motors)



(B)

$T_1 = 1.0$	$T_2 = 0.409$	(Reduced to zero when motor starts)
$E_1 = 1.3$	$E_2 = 0.65$	
$H_1 = 5.0$	$H_2 = 3.4$	
$x = 1.0$	$r = 0.015$	

$\theta_{20} = 180$ degrees

Figure 10. Motor and generator starting from standstill with applied generator shaft torque

Speed versus time

Equations 17 and 18 are integrated once to obtain equations 1.

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Biased-Core-Current-Transformer Design Method

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THAT peculiar improvement in performance often occurred when a current-transformer core was divided into two parallel magnetic circuits, with different turns on each, has been well known for years, and the reasons for it have been understood in a general way. The calculation of performance of the transformer, however, has been a most baffling problem—one that could be worked out only on a tedious trial-and-error basis. The lack of a practical and straightforward method has been a serious handicap to full use of the method of construction, despite strong evidence that this method of construction, which is both practical and simple, would produce real improvement in performance.

The difficulty of calculation lies in the fact that the flux densities in the cores are different by an amount depending on the ratio and phase angle between the primary and secondary currents and that the ratio and phase angle depend in turn on the two flux densities.

Solution depends on the conception of series magnetizing impedances for the two magnetic circuits, representing the impedance curve functions in such a way that simultaneous solution is not tedious. The principal purpose of the paper is to develop a method of calculation which is sufficiently simple, yet sufficiently accurate, to be used in engineering design.

The conventional current-transformer core operates at a relatively low flux density (less than 1,000 gausses), because only in this way can the ampere turns required to circulate the flux in the core be kept to a sufficiently low value for high accuracy of current transformation. Unfortunately, however, magnetic materials generally have a low permeability at small values of flux; thus, if the flux could be greater, the permeability would be higher. The idea of supplying auxiliary biasing ampere turns from an independent source to raise the total flux density to a value where the core would have good permeability was conceived long ago, but has been little used in practice, partly because of the complications involved in supplying the bias, but mostly because it is by no means clear that the effective permeability will be raised to any easily determined value.

A method invented by Wilson[1] in 1929 supplies bias to a very small element of the core simply by passing the secondary conductor through a hole in the core. The improvement in performance is difficult to calculate with any degree of exactness, and is not so great as that obtained when the whole core can be biased. A method described by Boyajian and Camilli[2] has the disadvantage of requiring auxiliary apparatus for excitation.

The general method to be described in this paper is illustrated by Figure 1. The core is divided into two separate magnetic circuits. The primary winding links both, but (for the general case) the secondary main windings and the secondary biasing windings are wound separately on each core. Then the main windings on the two cores are connected series aiding and the biasing windings series opposing—an arrangement that will give the minimum of coupling between the total main secondary winding and the total biasing winding. This can be seen more clearly from Figure 1.

It is not obvious that the biasing winding can produce a flux density corresponding to maximum permeability; nor is it obvious that this maximum permeability would be the effective permeability which would govern the performance of the transformer; nor is it clear how the bias can be practically obtained. These difficulties have prevented wide practical application of the idea, although many patents have been issued on various schemes for using the idea.

A practical and almost obvious method for using the biasing idea shown generally in Figure 1 is the double core with a single secondary winding shown in Figure 2, in which the bias is obtained by bringing the secondary conductor through between cores. The biasing ampere turns are then proportional to the secondary current. This construction is obviously practical, but the calculation of flux density in the two cores, the effective permeabilities, and the resulting performance of the current transformer, present a most tedious problem. The calculation process is not fundamentally obscure, but, like any problem in parallel magnetic circuits, solution by conventional methods is a cut-and-try procedure, is incredibly tedious, and is not practical from an engineering design standpoint. Thus, although a structure has been devised which is practical, economical, and promises real improvements in performance, it has been impossible to apply it to advantage, because no method of calculation has existed whereby performance could be calculated. It has been impossible to determine analytically the proper proportions of the cores and the best degree of bias.

This paper will develop the theory of a method for calculating performance. Since the arrangements of Figure 1 with the main and biasing windings in series, and of Figure 2 and Figure 4, to be used later for the actual development of theory, are all identical fundamentally, the theory will be equally applicable to any one of them.

Theory of Operation

On closer examination of Figure 1, the following facts are evident, which will assist analysis of the operation. The

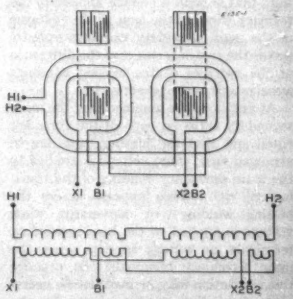

Figure 1. General construction of a biased-core current transformer

The primary winding H1–H2 links both the cores. The main secondary windings are connected series aiding and are labeled X1–X2. The biasing secondary windings are connected series bucking and are labeled B1–B2

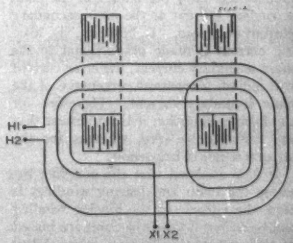

Figure 2. Practical construction of biased-core current transformer

Bias is secured from secondary current by having a few additional secondary turns around one core

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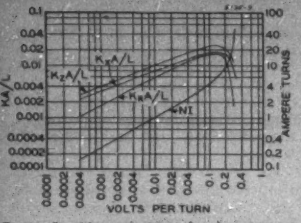

Figure 3. Nominal 60-cycle characteristic curves for the cores used in the tests and calculations

The ampere turns and the coefficients for the formulas for the resistance, reactance, and impedance of the equivalent series circuit for the core are plotted as functions of the volts per turn

main secondary windings in Figure 1 are connected in series aiding, and the secondary biasing windings are in series bucking; that is, with a voltage applied to the primary winding the sum of the voltages of the main secondary windings appears across the two in series, and the difference of the voltages of the biasing windings appears across the two in series.

At first it will be assumed that the main secondary turns on each of the cores are equal and that the biasing turns are so arranged that, when voltage is applied to the main secondary winding of the transformer, no voltage appears across the biasing winding; or conversely, when voltage is applied to the biasing-winding terminals, no voltage appears across the main secondary terminals. In practice this restriction may or may not be necessary, depending on the source for the biasing winding. If the coupling between the main and biasing windings is not zero, an error current will flow in the main secondary windings proportional to the current in the biasing winding. This error current can be used to compensate the transformer. If the biasing current does not vary with the main secondary current, this error current will become an increasingly large percentage of the main secondary current as the main secondary current decreases. If, however, the biasing current is made proportional to the main secondary current, the error current will remain a constant percentage of the main secondary current. Therefore, for the former condition it is important that the coupling be zero, whereas for the latter it is not so important.

If it is assumed that the coupling between the main and biasing windings is zero, the current in the biasing winding can be adjusted until the cores are biased at their point of maximum permeability without affecting the main secondary current. Various methods of supplying the biasing winding are possible, but the most usual one is simply to put it in series with the main secondary winding. This puts an additional burden on the main secondary winding, but for a small current transformer this will be less than five volt-amperes. Inasmuch as this burden is largely reactive, it usually will reduce the phase angle of the current transformer.

In an actual transformer, the windings will be arranged in a different manner from that just described. The two cores are put end to end with a spacer between them. The larger portion of the winding is wound about both cores, and then a few additional turns are wound about one core only. See Figure 2. This arrangement then can, by properly proportioning the turns, be made exactly equivalent to the arrangement in Figure 1.

The Derivation of the Mathematical Theory

The double-core current transformer is difficult to analyze, because simultaneous solution of the flux densities in the two cores must be made, and, unless a simple mathematical expression for the exciting current in terms of the induction is available, the equations cannot be solved. Any number of trial-and-error methods have been devised, all of which have been found to be impractical on account of the amount of numerical work involved. The method given in the following analysis is based on the equivalent circuit of Figure 4 (see Table I for explanation of the symbols). The arrangement of the windings in Figure 4 is fundamentally the same as in Figure 2, since the turns linking each of the cores are the same in the two figures. With the arrangement shown in Figure 4 the equivalent circuit for the transformer is much more apparent, as Figure 4 is essentially two current transformers in series. In the equivalent circuit the primary as well as the secondary windings are connected in series. The exciting impedance for each core is shown external to its transformer. In this analysis it was found more convenient to use an equivalent series circuit consisting of a resistance and reactance to represent the exciting-current branch. The fundamental procedure based on Figure 4 is as follows:

(*a*). Estimate the approximate value of the volts per turn per square inch in the core as the sum of the zero-burden biasing volts per turn per square inch (obtained from the biasing ampere turns per inch and a curve) plus the volts per turn per square inch required for the burden.

(*b*). Determine the resistance and reactance of the equivalent circuit for the cores from a curve, and, assuming the resistance and reactance to be constant, recalculate the volts per turn per square inch in each core. The use of a curve is the key to a rapid solution of the problem.

(*c*). Continue recalculating until the volts per turn per square inch calculated is that first assumed. This then represents the actual operating condition of the transformer. Usually the second calculation is sufficiently accurate.

(*d*). Calculate the transformer ratio and phase angle at the final values of volts per turn per square inch.

The principal reason this method has merit is that an initial value quite close to the actual value of volts per turn per square inch can be determined and that the resistance and reactance of the equivalent circuit for the core do not change too rapidly with changes in volts per turn per square inch. Usually the second estimate is sufficiently close to the final value.

An equivalent series circuit for the core was found to be the most convenient for this analysis. To obtain the curve we must secure a general expression for the resistance, reactance, and impedance of the equivalent series circuit for the core in terms of the volts per turn per square inch at 60 cycles as follows.

The flux density in the core is given by

$$B=\frac{E}{NA}\cdot\frac{1}{4.44f\,10^{-8}}$$

and, if $f=60$ cycles,

$$B=3.75\times10^{6}\left(\frac{E}{NA}\right)\text{ lines per square inch} \qquad (1)$$

The watts, volt-amperes reactive, and volt-amperes necessary for the core are

$$W=\left(\frac{W}{\phi}\right)\phi LA \qquad (2)$$

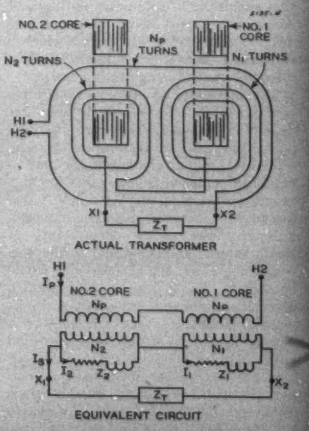

Figure 4. Arrangement of double-core current transformers used for development of the theory of calculation

The transformers are considered ideal, and the exciting branches, Z_1 and Z_2, are placed across the secondary windings of the transformers

$$VAR = \left(\frac{VAR}{\phi}\right) \delta l A \tag{3}$$

$$VA = \left(\frac{VA}{\phi}\right) \delta l A \tag{4}$$

The impedance of the equivalent circuit for the core is

$$Z = \frac{E^2}{(VA)} = \frac{E^2}{\left(\frac{VA}{\phi}\right)\delta l A} \cdot \frac{N^2 A}{N^2 A}$$

$$Z = \frac{N^2 A}{l}\left[\frac{\left(\frac{E}{NA}\right)^2}{\left(\frac{VA}{\phi}\right)^2 \delta}\right] \text{ohms} \tag{5}$$

The resistance component of this impedance is

$$R = Z\frac{W}{VA}$$

Substituting in this the values for Z, W, and VA from equations 5, 2, and 4, we find

$$R = \frac{N^2 A}{l}\left[\frac{\left(\frac{E}{NA}\right)^2}{\left(\frac{VA}{\phi}\right)^2 \delta}\right]\left(\frac{W}{\phi}\right)\left(\frac{VA}{\phi}\right)$$

$$= \frac{N^2 A}{l} \cdot \left[\frac{\left(\frac{E}{NA}\right)^2\left(\frac{W}{\phi}\right)}{\left(\frac{VA}{\phi}\right)^2 \delta}\right] \tag{6}$$

The equation for the reactance component of Z can be developed in a similar manner and is

$$X = \frac{N^2 A}{l} \cdot \left[\frac{\left(\frac{E}{NA}\right)^2 \frac{VAR}{\phi}}{\left(\frac{VA}{\phi}\right)^2 \delta}\right] \tag{7}$$

The quantities in the brackets in equations 5, 6, and 7 are only functions of the flux density in the core. For convenience they will be called K_Z, K_R, and K_X as follows:

$$K_R = \frac{\left(\frac{E}{NA}\right)^2\left(\frac{W}{\phi}\right)}{\left(\frac{VA}{\phi}\right)^2 \delta} \tag{8}$$

$$K_X = \frac{\left(\frac{E}{NA}\right)^2\left(\frac{VAR}{\phi}\right)}{\left(\frac{VA}{\phi}\right)^2 \delta} \tag{9}$$

$$K_Z = \frac{\left(\frac{E}{NA}\right)^2}{\left(\frac{VA}{\phi}\right)^2 \delta} \tag{10}$$

These constants, K_R, K_X, and K_Z then can be plotted in curve form. The equation for the impedance can be written

$$Z = \frac{N^2 A}{l} \quad K_Z = \frac{N^2 A}{l}(K_R + jK_X) \tag{11}$$

$$K_Z = K_R + jK_X \tag{12}$$

It will also be necessary to know the volts per turn per square inch induced as a function of the ampere turns per inch. This is developed as follows.

The exciting current for the core is

$$I = \frac{VA}{E} = \frac{\left(\frac{VA}{\phi}\right)\delta l A}{E}$$

Solving equation 10 for VA/ϕ, substituting it in the above equation, and rearranging the terms gives

$$\frac{E}{NA} = K_Z\left(\frac{NI}{l}\right) \tag{13}$$

It is also possible then to plot as a function of E/NA, the value of NI/l which, as will be explained, leads to solution of the problem.

In the equivalent circuit of the double-core current transformer as shown in Figure 4, it is assumed that the mean lengths of flux paths are equal.* N_1 is greater than or equal to N_2, but A_1 can be greater than, equal to, or less than A_2. The transformers also are assumed to be ideal and their exciting impedances represented by shunt impedances external to the transformers. It is desired first to develop three sets of equations:

(*a*). For calculating the volts per turn per square inch in each core for values of K_Z corresponding to estimated values of volts per turn per square inch.

(*b*). For estimating the approximate values of volts per turn per square inch in each core for the first try in (*a*).

(*c*). For calculating the ratio and phase angle when the actual values of volts per turn per square inch have been determined.

From Figure 4, the following equations may be written

$$N_1(I_S + I_1) = N_2(I_S + I_2) \tag{14}$$

Table I. 200-to-5-Ampere Current Transformer, Biased-Core Through-Type Construction

Burden: 2.5 VA, 90 Per-Cent Power Factor
Frequency: 60 Cycles

Data	Per-Cent Current	Per-Cent Ratio	Phase Angle, Minutes
*	100	100.17	+ 3
*	10	100.34	+13
**	100	100.06	+ 3
**	10	100.23	+13
†	100	100.07	— 1
†	10	100.17	+16
††	100	100.22	+ 9
††	10	100.45	+26

* Calculated values from nominal core data using method of this paper.

** Calculated values corrected for ratio instability, —0.11 per cent, due to cores with different characteristics.

† Test values of actual transformer as a biased current transformer.

†† Test values of actual transformer as an unbiased current transformer.

$$I_S Z_T = I_1 Z_1 + I_2 Z_2 \tag{15}$$

Solving equations 14 and 15 simultaneously for I_1 and I_2 yields

$$I_1 = I_S \frac{N_2 Z_T - (N_1 - N_2) Z_2}{N_1 Z_1 + N_2 Z_2} \tag{16}$$

$$I_2 = I_S \frac{N_1 Z_T + (N_1 - N_2) Z_1}{N_1 Z_1 + N_2 Z_2} \tag{17}$$

$E_1 = I_1 Z_1$. Substituting in this equation the value of I_1 from equation 16 and the values of Z_1 and Z_2 from equation 11, yields

$$\frac{E_1}{N_1 A_1} = \frac{I_S K_{Z1}}{l}\left[\frac{lZ_T + (N_1 - N_2) N_2 A_2 K_{Z2}}{N_2 A_2 K_{Z2} + N_1 A_1 K_{Z1}}\right] \tag{18}$$

Similarly,

$$\frac{E_2}{N_2 A_2} = \frac{I_S K_{Z2}}{l}\left[\frac{lZ_T + (N_1 - N_2) N_1 A_1 K_{Z1}}{N_2 A_2 K_{Z2} + N_1 A_1 K_{Z1}}\right] \tag{19}$$

With equations 18 and 19, if the values of K_{Z1} and K_{Z2} for the cores are known, the values of volts per turn per square inch can be calculated. It is necessary to know initially an approximate value for the volts per turn per square inch in each core so as to have some place from which to start. Equations 18 and 19 now will be modified, so that approximate values can be calculated.

If equations 18 and 19 now are rewritten, assuming that $K_{Z1} = K_{Z2} = K_Z$,

$$\frac{E_1}{N_1 A_1} = \frac{I_S Z_T}{N_2 A_2 + N_1 A_1} - \left[\frac{I_S (N_1 - N_2) N_2 A_2}{l(N_2 A_2 + N_1 A_1)}\right] K_Z \tag{20}$$

$$\frac{E_2}{N_2 A_2} = \frac{I_S Z_T}{N_2 A_2 + N_1 A_1} + \left[\frac{I_S (N_1 - N_2) N_1 A_1}{l(N_2 A_2 + N_1 A_1)}\right] K_Z \tag{21}$$

The first terms in each equation may be calculated now, but the last terms still contain K_Z. The last term in each equation is a function of the secondary current and the difference in turns between the two cores; or in other words, it is proportional to the biasing ampere turns. This can be shown as follows: rewriting equations 16 and 17, substituting in the values of Z_1 and Z_2 from equation 11, letting $K_{Z1} = K_{Z2}$, and multiplying the equations respectively by N_1/l and N_2/l gives:

$$\frac{N_1 I_1}{l} = \frac{I_S Z_T}{(N_2 A_2 + N_1 A_1) K_Z} - \left[\frac{I_S (N_1 - N_2) N_2 A_2}{l(N_2 A_2 + N_1 A_1)}\right] \tag{22}$$

$$\frac{N_2 I_2}{l} = \frac{I_S Z_T}{(N_2 A_2 + N_1 A_1) K_Z} + \left[\frac{I_S (N_1 - N_2) N_1 A_1}{l(N_2 A_2 + N_1 A_1)}\right] \tag{23}$$

If equations 22 and 23 are multiplied through by K_Z, they are identical to equations 20 and 21. That the left-hand terms also should be equal was shown by

equation 13. The last terms of equations 22 and 23 then represent the approximate biasing ampere turns per inch for each of the cores. From equation 13 it is seen that the last terms of equations 20 and 21 then can be read from the curve where the volts per turn per square inch are a function of the ampere turns per inch. Equations 20 and 21 then may be rewritten in functional notation where the last term of each equation is read from the curve as a function of the ampere turns per inch.

$$\frac{E_1}{N_1A_1} = \frac{I_S Z_T}{N_2A_2+N_1A_1} - f\left[\frac{I_S(N_1-N_2)N_2A_2}{l(N_2A_2+N_1A_1)}\right] \quad (24)$$

$$\frac{E_2}{N_2A_2} = \frac{I_S Z_T}{N_2A_2+N_1A_1} + f\left[\frac{I_S(N_1-N_2)N_1A_1}{l(N_2A_2+N_1A_1)}\right] \quad (25)$$

For the first approximation it is sufficiently accurate if only the arithmetic sum of the two terms is taken.

With the values of E/NA, calculated by equations 24 and 25, the values of K_g may be read from the curve and new values of voltage determined from equations 18 and 19. Sufficient calculations are made until no further significant changes in the voltages result. Usually only two calculations are required.

The actual transformer ratio then can be calculated when the correct values of voltage have been determined. The reversed primary current then is

$$N_pI_p = N_2(I_S+I_2) \quad (26)$$

Substituting in the value of I_2 from equation 17 and using the values for Z_1 and Z_2 from equation 11 yields

$$N_pI_p = I_S\left[N_2+\left(\frac{lZ_T+(N_1-N_2)N_1A_1K_{g_1}}{N_2A_2K_{g_2}+N_1A_1K_{g_1}}\right)\right] \quad (27)$$

This equation will reduce to the form:

$$N_pI_p = I_S(N_2+a+jb) \quad (28)$$

where a is the real part of the last term of equation 27, and b is the imaginary part. Both a and b are usually small compared to N_2. If the name-plate ratio is npR, the transformer ratio is approximately

$$\text{per cent } R = \frac{N_2+a}{(npR)N_p} \times 100 \quad (29)$$

and the transformer phase angle is

$$\text{phase angle} = -\frac{b}{N_2+a}\,3{,}438 \text{ minutes} \quad (30)$$

The negative sign is introduced by virtue of the definition of phase angle. That is, the transformer phase angle is positive if the secondary current leads the reversed primary current.

The nominal per-cent ratio at zero burden and cores of equal characteristics is a useful equation for estimating the ratio. In equation 27 let $Z_T=0$ and $K_{g1}=K_{g2}$

$$N_pI_p = I_S\left[N_2+\frac{(N_1-N_2)N_1A_1}{N_2A_2+N_1A_1}\right] \quad (31)$$

Hence, the nominal per-cent ratio is

$$\frac{N_2+\dfrac{(N_1-N_2)N_1A_1}{N_2A_1+N_1A_1}}{(npR)N_p}100 \quad (32)$$

If the two cores in the transformer are better or worse than they are supposed to be nominally, they have a considerable effect on the ratio and produce a phenomenon we might call "ratio instability." With reference to equation 27 the per-cent ratio is

$$\text{per cent } R = \frac{100}{N_p(npR)} \times \left[N_2+\frac{lZ_T}{N_1A_1K_{g_1}+N_1A_1K_{g_1}}+\frac{(N_1-N_2)N_1A_1K_{g_1}}{N_2A_2K_{g_2}+N_1A_1K_{g_1}}\right]$$

The total derivative with respect to K_{g1} and K_{g2} is

$$\Delta \text{ per-cent } R = \frac{100}{N_p(npR)}\left[-\frac{lZ_T(N_2A_2\Delta K_{g_2}+N_1A_1\Delta K_{g_1})}{(N_2A_2K_{g_2}+N_1A_1K_{g_1})^2}+\frac{(N_1-N_2)N_1N_2A_1A_2(K_{g_2}\Delta K_{g_1}-K_{g_1}\Delta K_{g_2})}{(N_2A_2K_{g_2}+N_1A_1K_{g_1})^2}\right]$$

The only case considered will be that in which the first quantity in the brackets is small, which is so if either the burden Z_T or $N_2A_2\Delta K_{g2}+N_1A_1\Delta K_{g1}$ is small. Simplifying the last term of the foregoing expression by letting N_1, N_2, $N_p(npR)$ be about equal to each other, and K_{g1} and K_{g2} about equal to each other:

$$\Delta \text{ per cent } R = \frac{N_1-N_2}{N_1\left(2+\dfrac{A_1}{A_2}+\dfrac{A_2}{A_1}\right)} \times \left[\frac{\Delta K_{g_1}}{K_{g_1}}-\frac{\Delta K_{g_2}}{K_{g_2}}\right]100 \quad (33)$$

From equation 10 at constant induction

$$\frac{\Delta K_g}{K_g} = -\frac{\Delta\left(\dfrac{VA}{\phi}\right)}{\left(\dfrac{VA}{\phi}\right)}$$

$$\Delta \text{ per cent } R = \frac{N_1-N_2}{N_1\left(2+\dfrac{A_1}{A_2}+\dfrac{A_2}{A_1}\right)} \times \left[\frac{\Delta\left(\dfrac{VA}{\phi}\right)_2}{\left(\dfrac{VA}{\phi}\right)_2}-\frac{\Delta\left(\dfrac{VA}{\phi}\right)_1}{\left(\dfrac{VA}{\phi}\right)_1}\right]100 \quad (34)$$

$\Delta\left(\dfrac{VA}{\phi}\right)$ is the difference between the actual and the nominal volt-amperes per pound at some average point. $\Delta\left(\dfrac{VA}{\phi}\right)+\left(\dfrac{VA}{\phi}\right)$ is not constant at all inductions. Equation 34 is not an exact equation but is meant only as a guide to how accurately the cores must be matched. It is also valid only for low secondary burdens or where $\Delta\left(\dfrac{VA}{\phi}\right)\Big/\left(\dfrac{VA}{\phi}\right)$ for the two cores vary in opposite directions.

Another difficulty is immediately perceived; that is, as the diameter of the transformer is increased, N_1-N_2 must increase in order to keep the biasing flux density constant. This means that the nominal no-load ratio becomes even more erratic. The possibility of adjusting this no-load ratio by means of short-circuited turns of resistance wire on one core is entirely practical; and, if the unit is a bushing-type current transformer competing with a wound-type high-voltage current transformer, the expense in adjustment can be justified.

It has been postulated previously that, if the effective coupling between the main secondary winding and the biasing winding be zero, the biasing winding will act as an additional burden in series with the total secondary burden. If the following values are substituted in equation 27, they will fulfill the requirement for zero coupling:

$$N_1 = N+n;\ N_1 = N-n;\ K_{g_1} = K_{g_2} = K_g;\ A_1 = A_2 = A$$

where N is the main secondary turns per core and n the biasing turns per core. Figure 1 shows the arrangement assumed for this. The biasing winding is in series with the secondary.

$$N_pI_p = I_SN\left[1+\frac{Z_T+\dfrac{2n^2AK_g}{l}}{\dfrac{2N^2AK_g}{l}}\right] \quad (35)$$

From equation 11 it is seen that n^2AK_g/l would be the impedance of one of the biasing windings and twice that would be the impedance of the two in series. It is

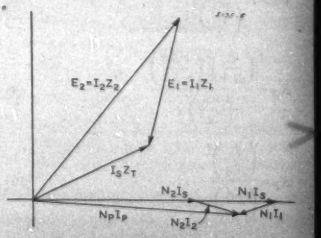

Figure 5. Vector diagram for double-core current transformer whose equivalent circuit is shown in Figure 3

E_1 and E_2 are the induced voltages of the current transformer secondary windings

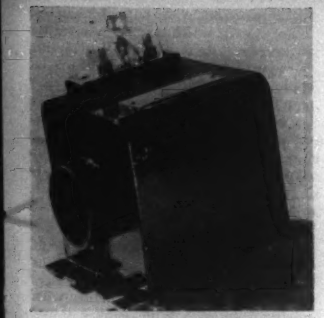

Figure 6. Type *FW* current transformer, 200-to-5-amperes ratio with double-core construction

This transformer has an accuracy class of 0.3 at a *B*-0.1 burden

to be noted that this impedance appears in equation 35 in series with the total secondary burden, Z_T. Also from equation 11, N^2AK_Z/l would be the impedance of one of the secondary main windings and twice that would be the impedance of the two in series.

For an ordinary current transformer with a series burden of Z_T' ohms, and a shunt exciting impedance of Z_X ohms, the ratio is

$$1+\frac{Z_T'}{Z_X} \tag{36}$$

If equation 35 is compared with equation 36, it is seen that the numerator of the last term of equation 35 corresponds to Z_T' of equation 36, the total series burden, and the denominator corresponds to Z_X, the shunt exciting impedance. It becomes apparent that the full permeability of the core at the point of bias is utilized, for K_Z is calculated on the basis of the a-c permeability at the point of actual operation. Also, it is apparent that the least variation in errors with secondary load or current will occur if K_Z is a maximum, or if the transformer is biased at the point of maximum permeability. Of course, instability of the nominal ratio according to equation 34 may be a factor in determining whether it is desirable to bias the transformer at so high an induction.

A vector diagram of the equivalent circuit of Figure 4 is shown in Figure 5. In general E_1 and E_2 are both large and about 180 degrees out of phase, the vector sum of the two voltages being equal to the voltage of the total burden. For high-power-factor burdens, the reversed primary current usually lags the secondary current, whereas for low-power-factor burdens it will lead.

In Figure 6 is a typical low-voltage through-type current transformer using the biased-core type of construction. This type of transformer has found much application in metering boxes where the through-type construction is convenient for the three-wire metering connection and makes possible changing transformer ratio by taking the primary conductor through the opening a number of times.

Experimental and Calculated Results

The following data are for the sample transformer used:

npR: 40 to 1; 200 to 5 amperes
$N_1 = 41$ turns
$N_2 = 39$ turns
$A_1 = A_2 = A$
$\Delta(VA/\phi)_2/(VA/\phi)_2 = -0.18$
$\Delta(VA/\phi)_1/(VA/\phi)_1 = -0.09$
Secondary resistance = 0.035 ohm

Figure 3 is the nominal curves for both cores. For this problem, the curves are plotted as follows:

Ampere turns as a function of volts per turn

$\frac{KA}{l}$ as a function of volts per turn

To use these curves, the equations are modified as follows:

Equation 13: $$\frac{E}{N}=\left(\frac{K_ZA}{l}\right)(NI) \tag{37}$$

If this equation is transposed, its significance is more apparent:

$$\frac{K_ZA}{l}=\frac{E}{IN^2}$$

which means that K_ZA/l is the exciting impedance measured at the terminals of N turns divided by the turns squared. K_ZA/l is K_ZA/l multiplied by the power factor and K_XA/l is K_ZA/l multiplied by the reactive factor. This shows how KA/l can be obtained from measurements on an actual winding on one core.

Equation 18: $$\frac{E_1}{N_1}=I_s\left(\frac{K_{Z1}A}{l}\right)\times\left[\frac{Z_T-(N_1-N_2)N_2\left(\frac{K_{Z2}A}{l}\right)}{N_2\left(\frac{K_{Z2}A}{l}\right)+N_1\left(\frac{K_{Z1}A}{l}\right)}\right] \tag{38}$$

Equation 19: $$\frac{E_2}{N_2}=I_s\left(\frac{K_{Z1}A}{l}\right)\times\left[\frac{Z_T+(N_1-N_2)N_1\left(\frac{K_{Z1}A}{l}\right)}{N_2\left(\frac{K_{Z2}A}{l}\right)+N_1\left(\frac{K_{Z1}A}{l}\right)}\right] \tag{39}$$

Equation 20: $$\frac{E_1}{N_1}=\frac{I_sZ_T}{N_2+N_1}-\left[\frac{I_s(N_1-N_2)N_2}{N_2+N_1}\right]\left(\frac{K_ZA}{l}\right) \tag{40}$$

Equation 21: $$\frac{E_2}{N_2}=\frac{I_sZ_T}{N_2+N_1}+\left[\frac{I_s(N_1-N_2)N_1}{N_2+N_1}\right]\left(\frac{K_ZA}{l}\right) \tag{41}$$

Equation 27: $$N_pI_p=I_s\left[N_2+\frac{Z_T+(N_1-N_2)N_1\left(\frac{K_{Z1}A_1}{l}\right)}{N_2\left(\frac{K_{Z2}A_2}{l}\right)+N_1\left(\frac{K_{Z1}A_1}{l}\right)}\right] \tag{42}$$

Equations 40 and 41 are the equations for the first estimation of the volts per turn in each core. The bracketed term of each of these equations is the biasing ampere turns for each of the cores. From equation 37 it is seen that when this is multiplied by K_ZA/l the result is the biasing volts per turn. This quantity may be read directly from Figure 3, where the ampere turns are plotted as a function of the volts per turn. The actual values of the volts per turn are found by repeated substitution in equations 38 and 39 and then the true primary ampere turns from equation 42. The per-cent ratio and the phase angle then may be determined by equations 28, 29, and 30. The results of these calculations are shown in the first two lines of Table I. The ratio must be corrected though, for the difference in the core characteristics according to equation 34. This correction is −0.11 per cent and the corrected values are shown in lines 3 and 4 of the table. The actual test values on the biased transformer also are given as well as tests as a straight unbiased transformer. For this latter condition, 40 turns linked each core.

Conclusions

A method of calculation for the double-core current transformer has been developed that is practical and has sufficient accuracy that the designer can determine the proper proportions of core and the best degree of bias to get the best possible performance, as well as the performance obtainable. It shows that much can be gained in reducing transformer ratio errors and in correcting phase-angle errors in bushing-type current transformers by using the double-core construction. This method of calculation also makes it possible to determine how closely the cores must be matched, and whether adjustment by test will be necessary. This will make possible the construction of high-accuracy bushing-type current transformers to smaller dimensions and lower primary-current ratings than was heretofore possible.

List of Symbols

Subscripts 1 and 2 refer to values for cores 1 and 2.

B—Induction in lines per square inch
E—Voltage across a given winding, volts

Impulse-Failure-Detection Methods as Applied to Distribution Transformers

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Synopsis: Investigation of several methods for the detection of impulse failures in distribution transformers has strengthened our belief in the inadequacy of the methods described in American Standard C57.2. All of the methods are discussed in detail, and the most hopeful one is compared with the present method of analyzing the voltage wave and making the physical observations as outlined in the Standards. Data are presented on transformers utilizing present and proposed methods.

DEMONSTRATION of the ability of electric apparatus to withstand impulse tests is of little value unless adequate failure-detection methods are used. Everyone who has had occasion to do impulse testing at one time or another has experienced some uneasiness concerning the certainty of detecting small failures when utilizing present testing technique as covered in the Standards. Many transformers have received impulse tests as a condition of specification and purchase to demonstrate the ability of their windings to withstand such tests. Examination of the windings after testing has disclosed failures which had not been suspected from any known failure indications. Since such a procedure is impractical and often impossible because of economics, it becomes necessary to revise impulse-testing technique relative to failure detection so as to acquire an accurate knowledge of the true condition of windings after impulse voltages have been applied.

Present Impulse-Failure-Detection Methods

For many years now it has been the practice to follow the testing procedure covered in American Standard C57.2, 10.122. This reference is quoted here for convenience.

"Detection of Failure During Impulse Test. Because of the nature of impulse-test failures, one of the most important matters is the detection of failure. There are a number of indications of insulation failure. Some of these are: noise within the transformer; presence of smoke; excessive current or drop in voltage in the excitation circuit as indicated by the magnetic oscillograph; failure of the gap or bushing to flash over, although the oscillogram indicates a chopped wave; presence of oscillations or other variations from the expected wave shape as indicated by cathode-ray oscillograms."

It may be seen that certain electrical observations are required, such as the wave shapes of the applied impulse by means of cathode-ray oscillograph by comparison between reduced-full-wave and full-wave oscillograms, and also inspection of the normal-frequency disturbance occasioned by normal-frequency follow current which may be initiated by an impulse failure. In addition to this there are such physical observations to be made as the notation of unusual sound and the presence of smoke or bubbles occasioned by arcing within the apparatus.

Experience With Present Impulse-Failure-Detection Methods

The experience cited here is the result of the test and examination of a great many small distribution transformers which were tested to destruction with impulse voltages. With smaller transformers, the ratio of capacitive impedance to inductive impedance is much smaller than is the case with larger power transformers. Therefore, the problems involved in impulse-failure detection are different. Superimposed high-frequency oscillations[1] rarely occur on the crest of the applied voltage wave as they do in the case of power transformers, so that meticulous examination of the voltage wave near its front is of little help in failure detection in small transformers. Likewise, the examination of the applied voltage wave on its tail yields unpredictable results, in some cases actually showing a shortening of the tail due to a layer failure, while in other instances revealing a considerable portion of the coil to be short-circuited out in the failure

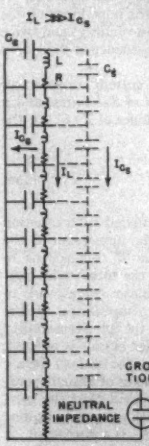

Figure 1. Equivalent circuit of idealized power-transformer winding

N_p—Primary turns
N—Secondary turn in a given winding
A—Cross sectional area of a given core, square inches
W—Watts, core loss
VAR—Volt-amperes reactive, core loss
VA—Volt-amperes, core loss
δ—Density of core, pounds per cubic inch
l—Mean length of flux path, inches
R—Equivalent series resistance of core, ohms
X—Equivalent series reactance of core, ohms
Z—Equivalent series impedance of core, ohms
$W/\#$—Watts per pound core loss
$(VAR)/\#$—Volt-amperes reactive per pound core loss
$(VA)/\#$—Volt-amperes per pound core loss
K_R—See equation 8
K_X—See equation 9
K_Z—See equation 10
I—Exciting current in a given winding, amperes
I_s—Secondary current of current transformer, amperes
I_p—Primary current of current transformer, amperes
Z_B—Total secondary burden of current transformer winding resistance plus external burden ohms
npR—Transformer name-plate ratio
Per-cent R—Transformer per-cent ratio

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Paper 45-129, recommended by the AIEE committee on electric machinery for publication in AIEE Transactions. Manuscript submitted April 16, 1945; made available for printing May 21, 1945.

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without the tail of the voltage wave being altered.

Smoke and bubbles cannot always get out of buried layers with sufficient velocity to be noticeable to the observer and therefore are not a dependable failure-detection method. The presence of normal-frequency excitation confuses the oscillography with disturbances caused by arcing of isolating gaps and should not be considered as a dependable indicator of failure, since many transformers known to have failed on impulse have successfully withstood normal voltage.

The usual sequence of evidence secured during tests deliberately increased in kilovolts until failure occurs, with the present American Standards Association methods, is as follows:

1. Failure may occur without any of the indicators showing the occurrence of failure.
2. Failure is shown by slight changes in wave shape of the applied wave without bubbles, or
3. Bubbles become noticeable.
4. Normal-frequency current will follow through the impulse path as the applied impulse voltage is increased above normal test levels.

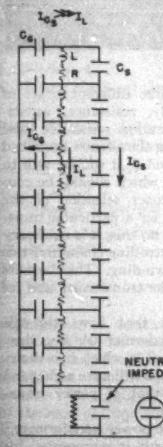


Figure 2. Equivalent circuit of idealized distribution-transformer winding

As a result of this experience, it is known that these methods of failure detection often will not show turn or layer failures or even the failure of major insulation to ground.

In view of such experience, we believe that the present procedures for fault detection are not satisfactory.

Investigation of Impulse-Failure-Detection Methods

In an effort to improve this situation, several impulse-failure-detection methods were investigated as applying to distribution transformers, with the aid of the electric transient analyzer, and the most promising were checked with the usual design of impulse generator. The work done with the transient analyzer is described in methods 1 to 8 inclusive, Table I, and the relative efficiency of the methods is tabulated in Table II. Methods 1, 2, 3, 4, and 5 consist of measurement of a voltage wave at some point in the transformer structure, whereas methods 6, 7, and 8 constitute current-wave measurements in the transformer neutral.

Table I. Description of Test Method

Method	Record Impulse Voltage Wave: Applied Wave C_1	Applied Wave C_2	Core	On Winding Tap	Low-Voltage Winding	Record Impulse Current Wave in Neutral Impedance Consisting of: Resistance	Capacitance	Shunt Capacitance and Resistance
1	x							
2		x						
3			x					
4				x				
5					x			
6						x		
7							x	
8								x

C_1 Impulse-generator capacitance—0.025 microfarad.

C_2 Impulse-generator capacitance—0.006 microfarad.

Table II

Efficiency of Testing—Method 1	2	3	4	5	6	7	8	Rating of Test Piece: Kva	Kv	Per Cent of Winding Failed
U	*F*	*E*	*P*	*E*	*F*	*E*	*E*	1.5	7.2	4.0
			P	—				1.5	7.2	8.0
G	*E*	*G*	*E*	*G*	*E*	*E*	*E*	5.0	2.4	12.0
			E					5.0	2.4	17.5
P	*E*	*F*	*G*	*F*	*E*	*E*	*E*	5.0	7.2	7.0
U	*P*	*F*	*G*	*P*	*F*	*E*	*E*	10.0	13.8	1.0
								10.0	13.8	3.0
E	*E*	*E*	*E*	*E*	*E*	*E*	*E*	25.0	2.4	16.0

Definition of method efficiency:
E—Excellent *G*—Good *F*—Fair *P*—Poor *U*—Unsatisfactory

Methods 1 and 2

Methods 1 and 2 consist of the observation of the applied voltage wave which is the present recommended procedure, except for the omission of normal-frequency voltage, for the determination of the electrical condition of a winding when subjected to impulse voltages. Method 2 employs a loosely coupled impulse generator; that is, a generator of small capacitance so as to have an inherently high regulation (voltage drop) as a result of a change in the impedance of the test piece brought about by the failure of its windings.

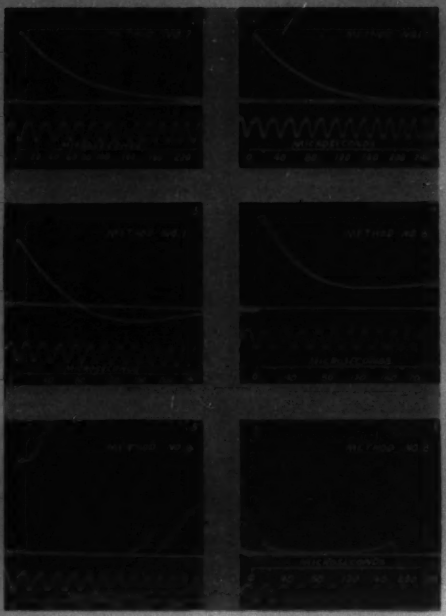
It was found that anything less than a generator capacitance of 0.006 microfarad was impractical, because it could not deliver a $1^1/_2 \times 40$ microsecond wave to low-impedance high-voltage windings. When the results of method 2 are compared with the results of method 1 (in Table II), in which the generator capacitance of 0.025 microfarad more nearly represents present testing practice, the advantage as far as failure detection is concerned lies with the low-capacitance generator (method 2).

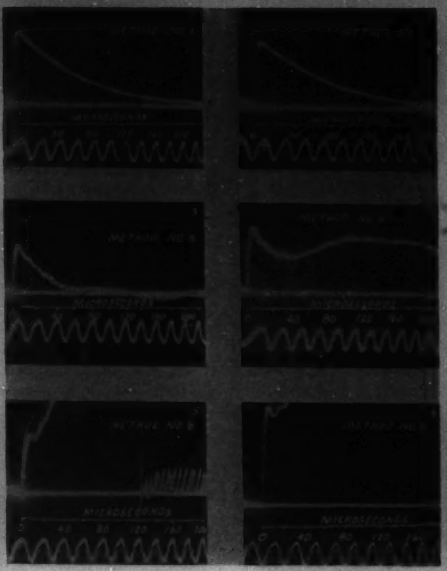
Method 3

Oscillations within the winding of a transformer can be recorded to some extent by measuring the voltage produced on its core. In general, this voltage is due to its capacitive coupling with the winding and is a reproduction of the applied wave plus some high-frequency oscillations. The magnitude of this voltage is a function of capacitance coupling and may be sufficiently high to stress unduly the insulation between core and coil. Although the method works very well in some cases, it should not be considered as a universal method of failure detection, because the utilization of this method involves the isolation of the core from ground which in itself produces voltage stresses unnatural to those experienced in conventional circuits.

Method 4

A modification of method 1 consists of the observation of the voltage at some other point in the same winding than that to which the wave is applied. This can be done where taps have been provided in the winding. The impulse voltage from tap to ground, when measured on the tap nearest the ground end of the





winding, in many cases changes substantially in both wave shape and magnitude at the occurrence of a failure. The utilization of this method is contingent on the presence of suitable taps within a given winding and the problem of bringing out of the tank an additional bushing not provided for in the design.

Method 5

This method involves the observation of voltage on a winding other than the one under test. This is equivalent to loose coupling in the impulse generator in that observation is made on a winding which is loosely coupled both electrostatically and magnetically with the winding to which the impulse is applied. In many cases, a layer failure in the high-voltage coil will change substantially the shape of the wave which is reflected in the low-voltage coil. Since one end of the low-voltage coil may be conveniently grounded during test, this method can be more readily adapted to impulse-failure detection than methods 3 and 4.

Measurement of Neutral-Impedance Current

Methods 6, 7, and 8

The dielectric condition of a winding during impulse testing can be determined by the measurement of the impulse current[1] as measured in a neutral impedance connected outside the transformer.

Figure 3 (left). 10-kva 2,400-volt transformer

Applied voltage wave

1. No failure
2. Failure of one turn (0.1 per cent)
3. Failure of ten per cent of winding

Impulse current

4. No failure
5. Failure of one turn (0.1 per cent)
6. Failure of ten per cent of winding

Figure 4 (right). 1½-kva 7,200-volt transformer

1. Applied voltage wave—no failure
2. Applied voltage wave—failure of 13¹/₂ per cent of winding (ground end)
3. Impulse current—no failure
4. Impulse current—failure of 0.02 per cent of winding (one turn)
5. Impulse current—failure of 13¹/₂ per cent of winding (ground end)
6. Impulse current—4¹/₂ per cent of coil short-circuited through 300.0 ohms

Changes in the impedance of the transformer winding due to impulse failure will bring about a change in the impulse current.

The use of a neutral impedance during impulse testing results in a circuit not encountered in actual transmission service. However, it should be stated that such a procedure does not alter perceptibly the impulse-voltage distribution within the transformer windings.

As there are three different types of impedance, namely, resistance, capacitance, and combination resistance and capacitance, used in the circuits described in methods 6, 7, and 8, it will be well to review the factors which should be considered in the proper selection of the neutral impedance for a particular transformer rating. To do this, it is necessary to consider the controlling characteristics of the transformer winding. This depends upon the size of the transformer and its voltage rating.

Impulse current that flows through a distribution-transformer winding during the time interval in which it is desirable to detect failures will have a changed distribution from that of power transformers.

In the case of the power transformers,[1] the equivalent circuit is represented by Figure 1, where a major part of the impulse current flows through the inductance–resistance circuit, as indicated by the bold lines of the circuit. Although no dividing lines can be drawn, distribution transformers in general would be represented more nearly by the equivalent circuit of Figure 2, where a major part of the impulse current flows through the capacitance circuit, as indicated by the bold lines of the figure.

As the measurement of impulse neutral current is accomplished by measuring the voltage drop across a neutral impedance which is placed in series with the transformer under test, and as this circuit is a voltage-divider arrangement, it is ad-

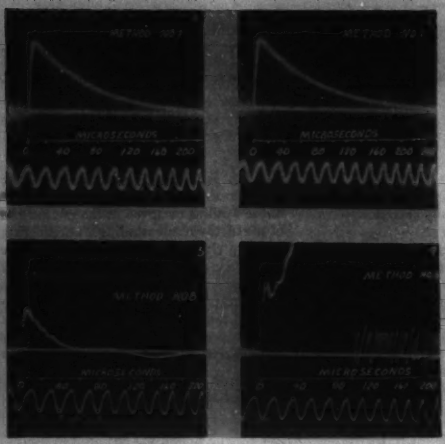


Figure 5. 1½-kva 7,200-volt transformer

Applied voltage wave
1. No failure
2. Failure of 2.0 per cent of winding

Impulse current
3. No failure
4. Failure of 2.0 per cent of winding

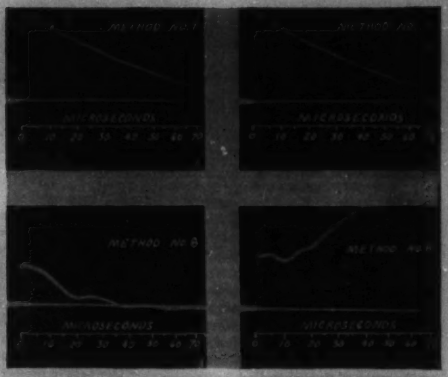


Figure 6 (upper right). 3-kva 7,200-volt transformer

Applied voltage wave
1. No failure
2. Failure of 50 per cent of winding (ground end)

Impulse current
3. No failure
4. Same failure as in oscillogram 2

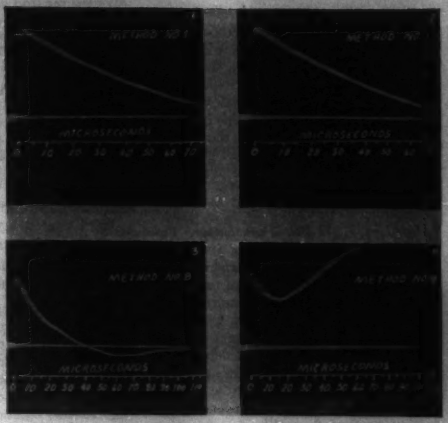


Figure 7 (right). 37½-kva 13,200-volt transformer

Applied voltage wave
1. No failure
2. Failure of 33⅓ per cent of winding (line end)

Impulse current
3. No failure
4. Same failure as in oscillogram 2

vantageous to match the neutral impedance with the controlling impedance of the transformer network. In other words, the desirable neutral impedance consists of a resistance[1] or an inductance in the case of large transformers, Figure 1, and a capacitor in the case of small distribution transformers, Figure 2. When a capacitor is used for a neutral impedance, the charge increases as long as current flows, and there is a tendency to increase the amplitude of the trace on the oscillogram. The use of a resistor in shunt with the capacitor helps to drain off the charge, thereby improving the oscillography and at the same time providing a discharge circuit for the capacitor.

Method 6 evaluates this current by measuring the voltage across an impedance consisting of a resistor placed in the transformer-winding neutral.[1] As most of the current is charging current, a pure resistance shunt will give a very large initial deflection. This peak current is of little value in failure detection, and so some means such as gaps has to be devised to protect the oscillographic equipment.

Method 7 utilizes a capacitor as the neutral impedance. This gives a very sensitive failure-detection method. An impedance change, caused by the short-circuiting of one layer (seven per cent) of a high-voltage coil, caused the impulse current to increase 3,300 per cent. A disadvantage of this method is that the capacitor charge continues to increase for a considerable time, particularly if isolating gaps are used between the test piece and the testing circuit. If isolating gaps are used, the capacitor cannot discharge except by leakage.

In method 8 it was found that a resistor could be used in shunt with the capacitor without appreciably reducing the sensitivity of the scheme. This method is an improvement of methods 6 and 7, and in the work done, a *time constant* of this capacitor-resistor combination of 100 microseconds or less was found to be satisfactory.

Experience in the Application of Methods 1 and 8

Tests on Transformers With Controlled Faults

In order to study impulse-failure detection where turn and layer failures are involved, it was necessary to provide full-scale transformers with a single turn and some portion of the layers brought out so that turn or layer failures could be arranged at will; otherwise a great many transformers might have to be tested to get the type of failure desired.

The data presented on these transformers were obtained using the present ASA method 1, and the best of the methods, as outlined in Table II, method 8. Circuit diagrams for these methods are shown in Figures 8 and 9. The oscillograms shown in Figures 3, 4, and 5 were taken on transformers having such con-

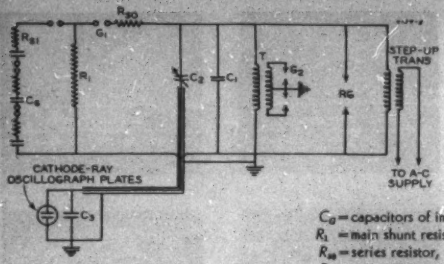


Figure 8. Conventional impulse test circuit for distribution transformers

C_0 = capacitors of impulse generator
R_1 = main shunt resistor
R_{so} = series resistor, external to generator
R_{s1} = series resistor, internal to generator
C_1 = auxiliary capacitor to control wave shape
C_2 = main capacitor of voltage divider
C_3 = auxiliary capacitor of voltage divider
G_1 = protecting gaps (high-vacuum)
T = transformer under test
G_2 = gaps to protect low-voltage winding
RG = test gap (rod gap)

trolled points of failure while using a conventional impulse generator of ASA recommended voltage level for the particular transformer voltage class. It was necessary to omit normal-frequency voltage because of the controlled faults.

10-Kva 2,400-Volt Transformer, Figure 3. When testing with method 1 turn failures could not be detected, but a layer failure is indicated by a shortening of the tail of the wave. The impulse current, method 8, readily detects both the turn and layer failures. In this instance, it was necessary to protect the oscillograph equipment by means of gaps. It would have served the same purpose to reduce the resistivity of the current-measuring impedance.

1½-Kva 7,200-Volt Transformer, Figures 4 and 5. Because of its higher voltage rating, this transformer has a considerably larger number of turns and layers than the ten-kilovolt-ampere 2,400-volt transformer shown in Figure 3. Oscillograms 1 and 2 in Figures 4 and 5 show that method 1 will not detect failures involving either 2 or 13½ per cent of the winding by observing the applied voltage wave. The impulse-current detection, method 8, readily detects either defect, as shown in Figures 4 and 5. It is also to be observed in this case that this method shows a one-turn failure very effectively (see Figure 4, oscillogram 4). As the detection of failure using the impulse-current method is contingent on being able to observe current changes due to impedance changes of the circuit brought about by failures within the winding, it is important to demonstrate that this method will detect failures even though this current is relatively small. To do this, a 4½-per-cent winding fault was closed through a 300.0-ohm resistance (see Figure 4, oscillogram 6).

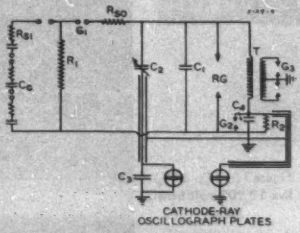


Figure 9. Recommended impulse test circuit for distribution transformers

C_0 = capacitors of impulse generator
R_1 = main shunt resistor
R_{so} = series resistor, external to generator
R_{s1} = series resistor, internal to generator
C_1 = auxiliary capacitor to control wave shape
C_2 = main capacitor of voltage divider
C_3 = auxiliary capacitor of voltage divider
G_1 = protecting gaps (high-vacuum)
RG = test gap (rod gap)
C_4 = capacitor of impulse-current-measuring shunt
R_3 = auxiliary resistor of impulse-current-measuring shunt
G_{2a} = gap to protect oscillograph
T = transformer under test
G_3 = low-voltage protective gap

Tests on Transformers in Which the Faults Developed During Testing

Oscillograms shown in Figures 6 and 7 are actual breakdown tests on developmental transformers built for that purpose. In these cases, the transformers were excited at normal-frequency voltage. However, the voltage wave shapes recorded on oscillograms 1 and 2 of Figures 6 and 7 are tests made in addition to the ASA method with normal-frequency voltage purposely omitted to avoid confusing the oscillography by the arcing of isolating gaps.[1]

3-Kva 7,200-Volt Transformer, Figure 6. In this case, a failure of 50 per cent of the winding occurred at the ground end of the high-voltage winding. Oscillogram 4 definitely indicates a failure by the neutral-current method. Oscillogram 2 does not indicate a failure although this oscillogram was recorded after the winding had failed, as shown in oscillogram 4. This was a consistent failure, and this condition was observed on many repeat tests.

37½-Kva 13,200-Volt Transformer, Figure 7. In this case, a failure of 33⅓ per cent of the winding occurred at the line end of the transformer. Here again, the current method, film 4, shows the failure, but oscillogram 2 for the potential method 1 cannot be interpreted to indicate a failure, although this test followed the current test. Here also, many checks were made to verify this finding.

Conclusions

1. The observation of changes in the impulse-voltage wave cannot be depended upon to indicate a fault in transformers.

2. The use of normal-frequency excitation in conjunction with impulse testing as a means of fault detection cannot be justified, on the basis of either the data submitted here or experience obtained in the past.

3. Smoke or bubbles are difficult to detect in small transformers with compact and buried layers and therefore cannot be depended upon to indicate impulse failure.

4. The utilization of the present ASA methods of fault detection will not detect a very large percentage of failures.

5. The observation of voltage across a neutral impedance in which impulse neutral current flows in a relatively simple and effective method of impulse-failure detection and therefore is recommended for inclusion in the test code.

Reference

1. Progress in Impulse Testing of Transformers, J. H. Hagenguth. AIEE Transactions, volume 63, 1944, pages 999–1005.

When the Welding Load Outgrows the Distribution Power Supply

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Synopsis: The ability of a 2,300–4,000-volt distribution system to supply single-phase a-c welders is limited not only by current-carrying capacity, but also by voltage regulation. The voltage limitations are reviewed and methods suggested for increasing the limits by changes in the power system and the customers' installations. Three types of subtransmission connections are described for use when the welding load outgrows the distribution power supply.

SINCE THE BEGINNING of World War II there has been a very rapid increase in both the size and number of electric welders in operation. Not only are they used in large numbers and in many sizes for large-scale production in industrial plants, but individual units and small groups of welders are being used for light manufacturing and for repair work in the smaller shops. A large portion of these welders are of the single-phase a-c resistance or arc types. The power factors are relatively low, and the loads are highly fluctuating in character.

In specifying the type of power supply for these welders, the power-company engineers have encountered certain system limitations which would not apply in serving an equivalent steady three-phase load. Service to single-phase welding loads from the usual 2,300–4,000-volt distribution system can be permitted only under favorable combinations of locations, welder sizes, and operating sequences.

The expense of a connection from a subtransmission system frequently may be avoided by modifications to the existing distribution supply or the customer's installation. In other cases, the size, characteristics, and location of the welder load are such that it is necessary to make a connection from the subtransmission system.

This paper will review some of the more commonly encountered limitations of the 2,300–4,000-volt distribution system and modifications of existing power systems and customer installations to permit serving welding loads and will describe some of the more common types of higher-voltage power supply for the larger welding loads.

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Limitations of the Existing 2,300–4,000-Volt Distribution System

The two principal system limitations are those due to

A. Lighting flicker at adjacent customers caused by the fluctuating characteristics of welding loads.

B. Delivery of sufficient voltage at the welder to permit satisfactory operations.

Both of these limitations are due to the inherent impedances of the power system, including the customers wiring for each location. Attention is called to the fact that all references in this paper to the power-system impedance include the entire electric system to the welder input terminals.

The annoyance from lighting flicker is dependent upon both the magnitude of the voltage fluctuation and the frequency with which it occurs, or at which the welding load is applied. The most critical frequency is of the order of six times per second, and the annoyance is progressively less for slower operations. The Duquesne Light Company uses the following limits for voltage fluctuation where lighting service is affected, based upon tests and operating experience over a number of years.

Frequency of Load Application	Volts (115-Volt Terms)	Per Cent
Over 1 per second	0.50	0.44
1 per second to 15 per minute	1.00	0.87
15 per minute to 3 per hour	2.00	1.74

The foregoing three frequency classifications correspond approximately to the frequencies of load and voltage fluctuations commonly encountered in electric welding. For example, seam and pulsation welders operate in the first frequency band. The second group includes many spot welders used for regular production work. The lower-frequency classification usually is applied to manually controlled welders, such as spot and a-c arc welders used for repair work or for very limited production. In order to insure the proper frequency classification, the customer is asked to furnish an estimate showing the proposed frequency of operation and welding load for each new installation.

In determining what voltage will be delivered at the welder, account must be taken of the total impedance from the welder to the sources of power. For the smaller welders, under 20 kva, the regulation of the substation, transmission, and power stations ahead of the local 2,300- or 4,000-volt circuit usually can be ignored.

Representative values of voltage regulation in 230-volt terms are shown in Figure 1 for typical 2,300-volt single-phase circuits, and also for several combinations of transformer and secondary wire sizes. The transformer regulation is based upon impedances of 2.6 per cent to 3 per cent for the sizes shown. The assumed spacing of conductors is 16 inches for 2,300-volt circuits and eight inches for 230-volt circuits. In this chart, a welding load of 50 amperes at 60-per-cent power factor has been assumed at the 220-volt welder input terminals. For practical purposes the voltage drops for other small low-power-factor welding loads would be approximately proportional to the currents assumed.

Primary and secondary distances are shown in feet, and the voltage drops for the primary circuit must be added to that for the transformer and secondary circuit to obtain the approximate voltage drop at the customer's service. An additional small allowance may be made, if desired, for the regulation ahead of the primary circuit and in the customer's wiring. Figure 1 is particularly useful in determining the power supply for small welders. The calculation time is reduced by the early elimination of high regulation methods.

In selecting a suitable power supply for the larger single-phase a-c resistance and arc-type welders, the usual approach is to calculate the voltage regulation at the welder for a number of supply methods. This procedure is simplified and the calculation time reduced through the use of the curves in Figure 2 to obtain the allowable power-system impedance for the proposed welder load.

These curves assume 200 volts at the welder input terminals with the welder in operation and 220, 230, and 240 volts at the welder input terminals with the welder out of service; 200 volts is the approximate lower limit of voltage usually supplied for 220-volt power service and is within the plus and minus ten-per-cent voltage range usually tolerated by the manufacturers.

The impedance values used in the curves are expressed in volts drop per ampere at 60-per-cent power factor in 230-volt terms. The impedance value from the curve then is compared with corresponding values, calculated by simple addition from tables or curves, for each supply method being considered. All high regulation methods can be

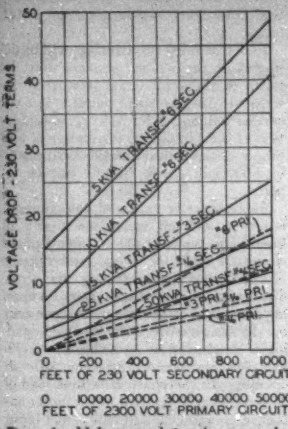

Figure 1. Voltage regulation due to supplying a load of 50 amperes at 60-per-cent power factor from a 230-volt single-phase service

eliminated easily in the early stages, and full attention can be concentrated on the low regulation methods. Separate calculations are necessary to determine if lighting flicker will result.

In working out welder problems, it is helpful to consider the welder as a load of variable impedance which can be adjusted within the limitation of the equipment design to draw a required kilovolt-ampere load from the line under a rather wide range of voltages. The relation between voltage at the welder and the impedance of the power system for a constant kilovolt-ampere load is illustrated in reference 3.

Corrective Methods to Permit Service From the Local 2,300–4,000-Volt Distribution Circuit

When a preliminary investigation shows that a given welder with specified duty cannot be tolerated at a proposed location due to excessive lighting flicker, or would not make satisfactory welds due to abnormal voltage regulation at the welder terminals, there are a number of changes which can be made either to the electric-supply system or to the customer's installation which often will eliminate the necessity for bringing in a service from a higher-voltage source. Some of these methods are described here.

Substitute 4,000-230-Volt Transformer for 2,300-230-Volt Transformer and Connect Between Phases

On the 2,300–4,000-volt system, a change in the welder supply from 2,300 volts to 4,000 volts doubles the substation impedance but does not increase the impedance of the primary circuit. For locations near the substation, the allowable load fluctuation is increased by only 50 per cent. At the end of long primary circuits, the substation impedance becomes negligible, and the allowable load fluctuation is increased by nearly 200 per cent.

Substitute a Three-Phase Star–Delta Transformer Bank for a Single-Phase 2,300–230-Volt Transformer

When a star–delta bank with a floating primary neutral is used, two thirds of the load is supplied from one phase of the primary circuit, and the drop in the neutral conductor has been eliminated. This again reduces the regulation to the distribution transformer. The allowable load fluctuation is increased by 50 per cent near the substation and by 200 per cent at the end of a long primary circuit. To obtain the same distribution-transformer regulation, 1–75-kva transformer would be replaced with 1–50-kva and 2–25-kva transformers, as two thirds of the load is supplied by one transformer.

Replace Primary Conductors

The replacement of conductors with those of larger size generally will be found more expensive than other methods, and the possible improvement is rather small due to the small change in regulation for low-power-factor loads. This method is seldom recommended to eliminate lighting flicker.

Replace or Relocate Distribution Transformers

A considerable improvement in regulation often can be obtained by replacing the distribution transformer with a larger size, also by relocation of the distribution transformer to reduce the length of the 230-volt secondary winding.

Install Independent Primary Circuits

In those cases where the principal problem is lighting flicker, this may be reduced considerably by installing independent primary conductors from the industrial plant back to some point on the electric supply system where the voltage fluctuation will be within the required limits.

Install Series Capacitor

A limited improvement may be obtained by installing a series capacitor in the primary circuit to compensate for part or all of the increase in primary-circuit regulation due to the welder load, but the protective equipment is expensive, and the space for mounting on poles in urban areas usually is limited. Improvement also can be obtained through the use of welders equipped with suitable series capacitors to reduce the kilovolt-ampere input for a given weld.

Install a Translator and Necessary Copper

Under certain conditions the translator described by R. O. Askey and E. R. Hendrickson,[4] is a very economical method of eliminating lighting flicker for other customers supplied from the same distribution circuit. The authors claim that 100-per-cent voltage correction results from the use of this device.

Distribute the Welders Over the Three Phases

The regulation of the primary circuit due to the operation of a single welder is the same as described for the star–delta bank. With a number of welders balanced between phases and operating at the same time, the primary-circuit regulation near the substation would be one third of that obtained when the same total load is served from one phase. At the end of a long primary circuit the regulation for the balanced welding load would be only one sixth of the single-phase value, due to division of load between phases and elimination of the neutral drop.

The transformer regulation due to a given single-phase welder supplied from a three-phase bank is greater than when it is served from a single-phase transformer of the same total capacity. With only one third of the welders connected to each phase, less advantage can be taken of diversity between welders than when all are supplied from one phase. Therefore, the three-phase service to a few welders may require more transformer capacity than the single-phase service. The size of transformers to supply a large number of welders usually is determined by the equivalent thermal loading.

Use Three-Phase Welders

A few installations of three-phase resistance-type welders have been made. This development should be watched carefully, since the three-phase balanced load which can be supplied from a three-phase power system is much larger than the single-phase value from the same system for the same frequency of load fluctuations. If it should operate in the cyclic flicker range, however, the permissible kilovolt-ampere demand might be less than for many of the conventional types of welders.

Use Storage-Type Welders

The instantaneous kilovolt-amperes drawn from the line are much less for the storage-type welders than for the conventional resistance welder. It is particularly applicable for certain types of welding, but to date the storage type has been costlier for many operations.

Install a Three-Phase Motor-Generator Set

The voltage fluctuations on the supply circuit can be reduced greatly by supply-

ing single-phase welding loads through a three-phase motor-generator set. The regulation of the generator and the cost of the added equipment limit the applications of this method.

Higher-Voltage Supply for the Larger Welding Loads

When it is necessary to serve a large number of small welders, or a small number of large welders, the possibilities for stretching the local 2,300–4,000-volt system often are exhausted. When this occurs it is necessary to provide some other system possessing greater capacity and a lower impedance in terms of the service voltage. Since the higher-voltage circuits are not found on nearly every street like the 2,300–4,000-volt distribution circuits, the connection from the higher-voltage circuit usually involves quite large expenditures.

The relatively low load factor of many welding loads makes it imperative that the most economical use be made of existing facilities. In this connection, there is a quite general feeling that welders should pay a fair share of the costs involved in serving them, but that they should not be penalized by requiring a more expensive installation than is necessary to protect the service to other customers.

A description follows of some typical 11-kv and 22-kv connections for welder loads which are beyond the modified 2,300–4,000-volt distribution-circuit limits.

Exclusive 2.3-Kv Circuit From Distant 22–2.3-Kv Station

There are two of these cases and both are supplied by single-phase circuits. In general if a three-phase exclusive distribution circuit is required for load or voltage reasons, then it might be as well to consider a single-phase transmission extension instead.

The first installation utilizes the spare 667-kva 22,000-to-2,300-volt transformer at one of the distribution substations, a 5,700-foot extension of two number-three wires, and a 75-kva 2,300–460-volt transformer adjacent to the customer's plant. This load was supplied initially over a regular circuit from the distribution substation, but changes in the customer's process resulted in complaints of lighting flicker. These were eliminated by connections as just described.

This method of correction is a wartime expedient and would not be utilized for a new installation in peacetime. Due to very large voltage regulation on this supply circuit, it is necessary to connect the electronic controls for the 200-kva welder to the lighting circuit, which is separate from the welding circuit.

The second installation consists of one 100-kva 22,000–2,300-volt transformer adjacent to a through transmission line, a 3,200-foot extension of two number-three wires, and one 100-kva 2,300–230-volt transformer adjacent to the customer's plant.

The main objection to this type of installation is the fact that it does not lend itself very well to growth. In general the impedance of the two transformers in series is a very large part of the total, and, if regulation is a problem, and it usually is, then this is not a satisfactory solution.

One analysis made prior to an expected change in welders resulted in the following comparison of voltage drops for four methods of reinforcement:

(*a*). 2,300-volt, single-phase—doubling the size of one transformer, 82 per cent drop as compared with present.

(*b*). 2,300-volt, single-phase—doubling the size of both transformers, 68.3 per cent drop as compared with present.

(*c*). 4,000-volt, single-phase—doubling the size of both transformers, 54.5 per cent drop as compared with present.

(*d*). 22,000-volt, single-phase—doubling the size of one transformer, 21.3 per cent as compared with present.

22-Kv or 11-Kv Customer's Substations for Welders Only

Six installations of this type are served from the 11,000- or 22,000-volt cable or overhead transmission system. These installations in general are single phase but may be three phase. Service is provided by a tap to the transmission system, using either cable or overhead wire, depending upon the district, and an air-break switch, fuses, transformer, and metering in the customer's substation.

This type of installation is very satisfactory and lends itself very nicely to growth merely by changing the size of the transformer and possibly replacing the fuses and metering current transformers with larger ones.

22-Kv or 11-Kv Customer's Substation for Power and Welders

These installations are three-phase by definition, since they involve three-phase power loads as well as single-phase welders. They may or may not require the same voltage for the welders and for power.

One installation consists of a three-phase cable tap and an air-break switch, fuses, 11,000–440–220-volt transformer bank and metering for both 440- and 220-volt services. Welders are supplied at 440 volts and motor load is supplied at 220 volts.

Another installation is similar except that fortunately the welders and power load are of the same voltage. Separate feeders are operated by the customer in his plant for service to the various power and welding loads.

Conclusions

The use of electric welding has been greatly accelerated during World War II. More general use of present types of welders and new developments in welding equipment and applications in the post-war period may necessitate changes in power-system design.

With the concentration of greater numbers of larger welders with automatic controls for high-speed production in individual plants, the voltage variation at the welder input terminals becomes very important. The regulation must be kept within small limits in order that the rejections will be small and that a uniformly high quality can be maintained in the finished product.

The increasing use of electronic controls and pulsation welding will require greater ingenuity by power-system engineers in the prevention of objectionable flicker at adjacent lighting customers. The annoyance from lighting flicker is dependent upon both the magnitude and frequency of the voltage fluctuations.

The important key to providing adequate voltage at the welder and prevention of lighting flicker is the design of the electric-supply system for relatively low impedance. The regulation at the welder is affected by the design of the power system and customer's wiring to the welder, but the lighting flicker is affected only by the design of that portion of the power system which is common to both the welding and lighting loads.

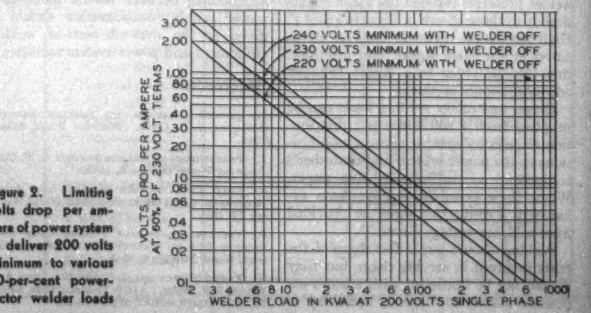

Figure 2. Limiting volts drop per amperes of power system to deliver 200 volts minimum to various 60-per-cent power-factor welder loads

An Interval and Dwell Tester for Bomb-Release Interval Controls

T. H. LONG
MEMBER AIEE

Synopsis: The device described is essentially a frequency meter with a scale proportional to the logarithm of 1/frequency, and a dwell meter suitable for use on inductively loaded contacts in d-c circuits. It has been found useful in several jobs in military aviation, one of which is described in some detail. An appendix gives a simple analysis of the shape of the frequency scale distribution obtained.

IN MILITARY AVIATION the device that originates the release impulses when a train (or series) of bombs is to be dropped is known as a bomb-release interval control. This bomb-release interval control (or interval control) receives its starting impulse either manually or automatically from the bomb-sight mechanism.

The usual interval control is adjustable as to speed at which the bombs are to be dropped; that is, the interval between the dropping of the bombs is preset on a dial graduated in feet of interval, opposite a ground speed scale graduated in miles per hour (or knots). The number of bombs to be dropped is preset on another dial, and after that the procedure can be automatic.

The interval range usually covered is from 7.3 to 147 feet at 100 miles per hour, corresponding to 1 to 20 release impulses per second. In the high-speed part of the range the duration of the release impulses becomes quite important, as each impulse must last long enough to operate the bomb-release mechanism, and the space between impulses must be long enough to permit a switching operation that automatically sends the next release impulse to the next bomb release.

This situation results in rather narrow tolerances on the operation of the interval control at short intervals, and, even though these tolerances are met at the factory, there has been no positive assurance that they still would be met when the device went into service. There has been still less assurance that they would be met after several months of service. In fact the effectiveness of bombing missions was being reduced by failure of bomb-release interval controls, mainly because there was no practicable method available for preflight tests.

Requirements for Instrument for Preflight Tests

It was believed that an instrument for adequate preflight testing should include an indicator that would give a direct reading of the interval between bombs, and another indicator that would give direct information as to the duration of contact and the "off time" between contacts. For short-interval operation the impulses from certain interval controls are originated alternately by two relays; so it is necessary to measure not only the average contact duration and spacing but also the average performance of each of two series of alternating contacts; that is, the average of the even-numbered impulses must be measured independently of the average of the odd-numbered impulses.

As the interval calibration must extend over a range of approximately 25/1 and should be reliable within at least five per cent throughout, it was essential that the scale be at least approximately logarithmic; and the divisions should correspond to the interval dial of the bomb-release interval control. Other requirements were that the instrument must be portable, small enough to be used in restricted space, durable, and essentially independent of ambient temperature.

As the performance of interval controls is influenced by applied voltage and by the nature of the load, it was necessary to include a voltmeter and an internal dummy load closely approximating the usual bomb release and average wiring.

It was expected that the instrument frequently would be used while the bomb racks of the airplanes were being loaded, and so it must be impossible under any circumstances for impulses from an interval control under test to reach the bomb releases.

A further requirement was that the equipment should operate with either 100-microfarad electrolytic or 1-microfarad paper snubbing capacitor across the load contacts of the interval control.

Interval and Dwell Tester

The basic design of the instrument to be described was developed as a direct-reading frequency and dwell meter in 1942 and demonstrated at Wright Field early in 1943. ("Dwell" as used here is the contact duration expressed as a per cent of the contact period.) The final instrument was almost identical to the original with the addition of a sorting circuit to make possible independent dwell measurements on the even- and odd-numbered impulses. The complete instrument is shown in Figure 1 in actual operation as a bench testing device, testing the 50-foot interval setting of the interval control in the foreground. Figures 2 and 3 are sketches illustrating the use of the interval and dwell tester to test an interval control mounted in a bombing plane.

The compartments shown on either side of the instrument panel hold the connection cords and spare fuses.

Interval Circuit

With reference to the circuit diagram of Figure 4, the interval circuit includes a small 45-volt radio B battery, low-temperature-coefficient resistors R_1, R_2, and R_c, damping capacitor C_1, and interval relay I, arranged alternately to charge and

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Much calculation time can be saved in the solution of both general and specific welder problems through the use of charts similar to those shown in Figures 1 and 2. High regulation methods can be eliminated in the early stages, and attention then can be given to a choice between adequate supply methods.

Larger and faster welding loads can be supplied from 2,300–4,000-volt distribution circuits by making certain modifications in the power system and customer's equipment, as outlined in this paper. When these possibilities have been exhausted, a connection must be provided from a higher-voltage circuit.

Welders should pay a fair share of the costs involved in serving them, but they should not be burdened with a more expensive installation than is necessary to insure satisfactory operations and to avoid complaints from lighting flicker. In choosing between several methods of power supply, consideration should be given to the over-all cost of welding equipment and power-system facilities.

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Figure 1. Interval and dwell tester in use as bench-instrument testing bomb-release interval control in foreground at 50-foot interval setting

discharge metering capacitors C_3 and C_4. The dummy load is connected between the lower point of S_1 and ground, with provision for the alternative use of an external load. Relay 1 is in parallel with either load so that each impulse takes capacitors C_3 and C_4 through a charge and discharge cycle. The dummy load is a five-ohm 200-watt resistance in series with an inductance. The inductance is a single-layer winding on a three-eighths-inch-diameter soft-iron rod ten inches long.

It is obvious that if C_1 is large enough that the cyclic variations in its voltage are negligible when relay I is operating, the discharge current i through metering capacitors C_3 and C_4 will be equal to fCe where

f = the impulse frequency
$C = C_3 + C_4$ in farads
e = voltage across C_1

If we ignore for the moment the current through the microammeter circuit which is in fact quite small, and assume that e is a small part of the battery voltage, then i will be approximately constant as it is limited by R_1. Then $e = i/fC$ and the scale is reciprocal with frequency, as the instrument deflection is proportional to e.

A reciprocal frequency scale is a linear-interval scale, and the lower part of the interval scale is substantially linear. For increasing intervals the scale becomes more condensed and is in fact a good approximation of a logarithmic scale, since i is reduced and e is increased until at full scale e is roughly 40 per cent of battery voltage. A more detailed analysis is given in the appendix.

Field calibration of the interval circuit is made by adjusting the instrument zero adjuster to a zero calibration mark, turning power on (S_3), opening calibrate switch (S_2), and setting the interval meter by an adjuster under the instrument (this is the potentiometer across the instrument) to a full-scale calibration mark. Switch S_2 then is released, the pointer swings off scale to the right, and the instrument is in calibration. This calibration eliminates any influence on interval readings that otherwise would result from changes in battery voltage or from the temperature coefficients of the instrument winding and its shunted potentiometer.

Temperature will affect the accuracy of the interval circuit by its effect on R_1, R_2, R_e, C_3, and C_4. A one-per-cent increase in capacitance or in resistance will reduce the interval reading by one per cent. The variation of capacitance within the operating-temperature range is somewhat irregular but on the order of one per cent. The temperature change in the resistance is of course below one per cent.

Dwell Circuit

The dwell circuit comprises an input potentiometer, a resistance-loaded selenium rectifier, an averaging circuit, and a microammeter calibrated in per-cent dwell. Switch S_4 and an external resistance make it convenient to use this instrument to check battery voltage so the instrument is also calibrated in volts.

At the usual operating voltage of 27 volts the input to the dwell circuit measures on the order of 500 ohms resistance so that it will have a negligible damping effect on the inductive kick from the six-ohm load circuit. This inductive kick is blocked out of the instrument circuit by the two disk rectifier. Dwell full-scale calibration is made by setting the input potentiometer for full-scale reading when a continuous forward voltage is applied from the interval-control power supply through switch S_4. The instrument then will read in proportion the average forward voltage of a series of impulses which is by definition the dwell in per cent. Of course, if the nature of the load were such that current interruption caused oscillations that become appreciably positive, this method of measuring dwell would be subject to some error, but the usual bomb release is definitely not of this type.

Under operating conditions the maximum reverse voltage that appears across the rectifier output is from 0.3 per cent to 4 per cent of the impressed reverse volt-

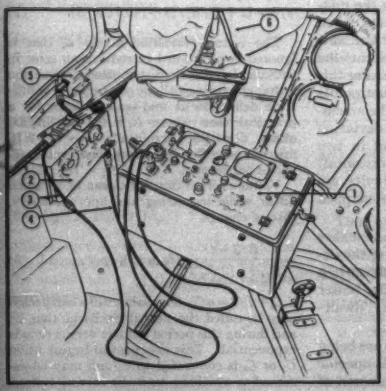

Figure 2 (left). Interval and dwell tester connected inside bomber

1—Tester
2—Interval control
3—Connection to power cable
4—Connection to interval control
5—Bomb-release switch
6—Bomb sight

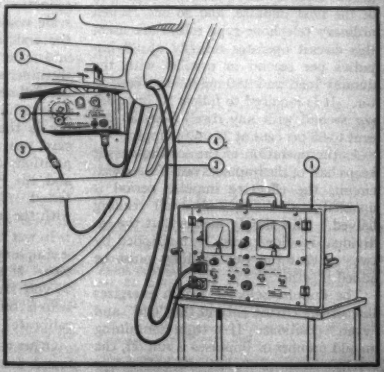

Figure 3 (right). Interval and dwell tester connected outside of bomber

1—Tester
2—Interval control
3—Connection to power cable
4—Connection to interval control
5—Bomb-release switch

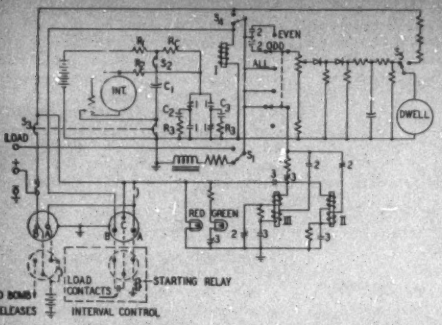

Figure 4. Circuit diagram of interval and dwell tester

The circuits associated with the interval and dwell tester are shown in broken lines

The impulse selector is shown in position to measure the dwell of odd-numbered impulses

age. With the internal load in use the error introduced by the rectifier is negligible, but if a 15-ampere solenoid is used there may be an error of about one per cent attributable to the rectifier.

As the dwell circuit only makes a comparison measurement it has no temperature error.

The dwell full scale must be recalibrated whenever the interval-control voltage changes. This is particularly important at short intervals since a one-volt increase can cause the dwell to change from 50 per cent to 53 per cent. If the dwell circuit is not recalibrated the dwell reading would change from 50 per cent to 55 per cent.

The sorting circuit alternately connects and disconnects the dwell circuit and the load in the idle time between impulses. This makes it possible to measure the dwell of even-numbered and odd-numbered impulses independently. This is accomplished by relays II and III in a modification of a conventional circuit in which the operation of relay III during an impulse changes the circuit to reduce the operating time of relay II at the end of that impulse. Then the operation of relay II sets up the circuit to reduce the release time of relay III at the beginning of the next impulse, and so on. When ordinary telephone-type relays are used, this circuit operates reliably at 30 impulses per second in parallel with the dummy load and 100-microfarad capacitor. It is required to follow 20 impulses per second with any dwell from 35 per cent to 65 per cent at 27 volts supply.

As the operation of the sorting circuit keeps half of the impulses out of the dwell circuit, the effective impulse period is doubled and the actual dwell reading halved. This simply means that the individual readings must be multiplied by two, or that the two readings must be added together.

The impulse selector switch energizes the sorting circuit only in the "odd" and "even" positions. If a train containing an odd number of impulses is run off, the sorting circuit will be left with both relays energized, and unless the circuit is "cleared" by momentarily operating S_4 (the dwell calibrate switch) the odd impulses in the next train will be read at the "even" switch position, and vice versa. Necessity for clearing is indicated when the green "clearance-for-sorting" light is out.

The impulse selector switch is of the short-circuiting type so that it is possible to switch back and forth from "odd" to "even" during a series of impulses without losing step.

Discussion

It has been found possible to keep the interval meters within three per cent of a printed scale calibration throughout the range in spite of instrument variations. This is done by setting the instrument zero adjuster and the potentiometer adjustment so the calibration is exact at intervals of 7.5 feet and 150 feet. Then two or three points in the middle of the scale are checked. Occasionally one will be more than three per cent low. To correct this the resistance of either R_1 or R_3 is reduced about 15 per cent by shunting with another resistor, and the process of line-up is repeated. This 15-per-cent reduction in resistance increases the mid-scale readings about four per cent when the ends are lined up, so that the new mid-scale readings will be within the three-per-cent limit. After checking this the full-scale and zero calibration points are established and marked. The assembly is then completed and a deviation card run on the interval circuit in two positions (panel vertical and horizontal) and the dwell and sorting circuits are tested. The deviation card is shipped with the instrument.

In wet climates the internal load makes it simple to dry out the interior of the device. It is only necessary to connect to a 20-volt storage battery, turn the power switch on, and tie down the "dwell–calibrate" switch (S_4).

Other uses of a similar nature are being found for this equipment. A specific example of this is in the measurement of the performance of the "peck" relay in the *C-1* pilot.

It should be understood in connection with possible other uses that the interval-meter circuit is restricted to a maximum frequency on the order of 30 cycles unless vacuum tubes are to be used. The present dwell circuit is not limited as to frequency, but for some applications a vacuum-tube circuit would eliminate frequent adjustments and errors caused by oscillations.

Appendix

In the following notation capacitors and resistors are identified by the same subscripts used in Figure 4:

f = contacts per second of any one contact of relay I

S = interval in feet at 100 miles per hour ground speed = $146.7/f$

C = capacitance of C_4+C_5 in farads

E = battery electromotive force, volts

e = volts across C_1

e_0 = volts across C_1 during calibration ($f=0$)

i = average current to C_4+C_5

i_1 = average current through R_1

i_2 = average current through R_2

R_1 includes battery resistance

R_2 includes instrument and shunt resistance

C_1 is assumed large in comparison to C_4+C_5

$$i = fCe \tag{1}$$

$$E = e + R_1 i_1 = e + R_1(fCe + e/R_2) \tag{2}$$

$$E/e = 1 + R_1(fC + 1/R_2) = \{R_2 + R_1(fCR_2 + 1)\}/R_2 \tag{3}$$

$$e/E = R_2/(R_1 + R_2 + fCR_1R_2) \tag{4}$$

$$e_0/E = R_2/(R_1 + R_2 + R_s) \tag{5}$$

$$e/e_0 = (R_1 + R_2 + R_s)/(R_1 + R_2 + fCR_1R_2) = (R_1 + R_2 + R_s)/(R_1 + R_2 + 146.7CR_1R_2/S) \tag{6}$$

if $R_1 = R_2\ (=R)$

$$e/e_0 = (2 + R_s/R)/(2 + 146.7CR/S) \tag{7}$$

The voltage variation across C_1 that is ignored in equation 1 introduces an error in the calculated scale distribution of equation 7 that amounts to about one per cent of full-scale deflection at mid-scale; this is for a practical case where $R_1 = R_2 = R = 139{,}000$ ohms, $C_1 = 31.5$ microfarads, $C_2 = C_3 = 2.16$ microfarads, $R_3 = 560$ ohms, and $f = 1$ to 30 cycles per second.

Voltage versus time for C_1 can be assumed linear while increasing and approximately, rate of change

$$= \frac{E/2 - e}{(C_1 + C/2)R/2} = fe/n \text{ volts per second} \tag{8}$$

if $C_1 + C/2 = nC$. The balance of a half period may be called the partial-discharge time T, and during this period voltage versus time is exponential. This exponential begins when C_4 or C_5 is connected to C_1 and may be assumed to continue until the rate of voltage

Symmetrical Components as Applied to the Single-Phase Induction Motor

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THIS PAPER is intended to show in detail the application of the method of symmetrical components to the solution of single-phase-induction-motor performance characteristics. By the use of this method single-phase-motor theory follows very closely the simpler case of the balanced polyphase-motor theory. The author of this paper is of the opinion that a clearer concept of the physical theory can be obtained as contrasted to other methods—either from the revolving-field or the cross-field concepts.

In their AIEE paper of May 1936, Lyon and Kingsley[1] ably presented this subject in a more general manner and also with particular emphasis on the motor having main and start phases not in space quadrature. Their work and the work of Mr. Morrill[2,3] form the basis of the thesis now to be considered.

Assumptions

1. The motor is magnetically symmetrical:
   (a). Sinusoidal distribution of conductors in the stator slots.
   (b). Uniform air gap.
   (c). Uniform iron permeance.
2. Sinusoidal voltage applied.
3. Linear constants—saturation of the iron flux paths is negligible.
4. Friction and windage, iron loss,[4] and load losses are subtractive from the rotor output.
5. Main and start phases are in space quadrature (90 electrical degrees between axes of these windings).

General Considerations

The solution of power or current flow in polyphase circuits when the applied voltages are not balanced, or when the load impedances are not equal can be accomplished best by the application of the method of symmetrical components. We will show presently that the case of the single-phase motor is a special case of an unbalanced two-phase motor.

Let us assume the general two-phase circuit with phase voltages (V_M and V_S) unequal in magnitude and not in time quadrature. It has been shown[4] that two balanced systems can be formed: one system, called the "positive sequence" (+) consists of components of V_M and V_S which are equal in magnitude and in time quadrature, and have positive (+) phase rotation or the same rotation as the V_M and V_S system; the other system, called the "negative sequence" (−) consists of other components of V_M and V_S equal in magnitude and in time quadrature, *but* phase rotation is opposite that of the positive-sequence components. No "uniphase" or "zero-sequence" components exist.

Part I

By definition we then have

$$V_M = V_M^+ + V_M^- \tag{1}$$

$$V_S = V_S^+ + V_S^- \tag{2}$$

$$V_S^+ = V_M^+ \angle 90^\circ = +jV_M^+ \tag{3}$$

$$V_S^- = V_M^- \angle 90^\circ = -jV_M^- \tag{4}$$

Phase S leads phase M in time angle. From equations 2, 3, and 4 we then have

$$V_S = j(V_M^+ - V_M^-) \tag{2a}$$

which defines V_S in terms of the components of V_M. When the magnitude and time phase of V_M and V_S are each known, the symmetrical components of each can be calculated by adding equation 1 and $-j$ times equation 2a and clearing

$$V_M^+ = \frac{V_M - jV_S}{2} \tag{5}$$

By subtracting $-j$ times equation 2a from equation 1 and clearing we have

$$V_M^- = \frac{V_M + jV_S}{2} \tag{6}$$

All the foregoing quantities are vectors representing rms magnitude and time phase voltages.

By the same procedure we arrive at current values:

$$I_M = I_M^+ + I_M^- \tag{7}$$

and

$$I_S = I_S^+ + I_S^- \tag{8}$$

$$I_S^+ = jI_M^+ \tag{9}$$

$$I_S^- = -jI_M^- \tag{10}$$

$$I_M^+ = \frac{I_M - jI_S}{2} \tag{11}$$

and

$$I_M^- = \frac{I_M + jI_S}{2} \tag{12}$$

In a general two-phase system as shown in Figure 1, Z_M and Z_S are the load impedances of phases M and S, respectively. Now applying Ohm's law, we have

$$V_M = I_M Z_M \tag{13}$$

and

$$V_S = I_S Z_S \tag{14}$$

Then from equations 13, 7, and 1,

$$V_M^+ + V_M^- = (I_M^+ + I_M^-) Z_M \tag{15}$$

and from equations 14, 8, and 2,

$$V_S^+ + V_S^- = (I_S^+ + I_S^-) Z_S \tag{16}$$

or from equations 3 and 4 equation 16 becomes

$$jV_M^+ - jV_M^- = (+jI_M^+ - jI_M^-) Z_S \tag{16a}$$

or

$$V_M^+ - V_M^- = (I_M^+ - I_M^-) Z_S \tag{16b}$$

Adding equations 15 and 16b we have

$$V_M^+ = {}^1/_2 [I_M^+ (Z_M + Z_S) + I_M^- (Z_M - Z_S)] \tag{17}$$

Subtracting equation 16b from equation 15 and clearing, we have

$$V_M^- = {}^1/_2 [I_M^+ (Z_M - Z_S) + I_M^- (Z_M + Z_S)] \tag{18}$$

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drop across C_1 (ignoring currents through R_1 and R_2) $= fe/n$.
Then

$$T = (R_1 C/2) \log_e (1/fR_1 C) \tag{9}$$

This varies from 0.0073 to 0.0032 second for f from 1 to 30 cycles per second. This makes the magnitude e_r of the voltage variation across C_1

$$e_r = (1 - 2fT) e/2n \tag{10}$$

Then from equation 1

$$i = fC(e + e_r/2) \tag{11}$$

and a more correct value of

$$e/e_0 = \frac{2 + R_c/R}{2 + 146.7CR[1 + (1 - 2fT)/4n]/S} \tag{12}$$

This reduced the one-per-cent error in scale distribution to about 0.25 per cent. The error was determined by establishing 13 frequencies to ±0.05 per cent by a tuning fork method and measuring the average current in the microammeter circuit by a resistance and potentiometer.

It will be seen that the interval-meter deflection is independent of the dwell, provided that the minimum duration of contact is greater than about $2T$.

In the case of a transformer or single-phase motor where there are not the same turns in each of the windings or phases then,

$$|I_S^+| = \frac{M}{S}|I_M^+| = \frac{|I_M^+|}{a} \tag{19}$$

and

$$|I_S^-| = \frac{|I_M^-|}{a} \tag{20}$$

$$V_S^+ = \frac{S}{M}|V_M^+| = a|V_M^+| \tag{21}$$

and

$$V_S^- = a|V_M^-| \tag{22}$$

where

M = effective conductors of the M phase
S = effective conductors of the S phase
$a = S/M$

We can now write

$$V_S^+ = jaV_M^+ \tag{3a}$$

$$V_S^- = -jaV_M^- \tag{4a}$$

$$V_S = ja(V_M^+ - V_M^-) \tag{2b}$$

similarly

$$I_S = j/a(I_M^+ - I_M^-) \tag{8a}$$

In a single-phase motor it is obvious that

$$V_S = V_M \tag{23}$$

Now equation 2b becomes

$$V_M = ja(V_M^+ - V_M^-) \tag{2c}$$

Furthermore, we will find that the impedance to positive-sequence currents is not the same as for negative-sequence currents in rotating apparatus.

Let

Z_M^+ = impedance to I_M^+
Z_M^- = impedance to I_M^-
Z_S^+ = impedance to I_S^+
Z_S^- = impedance to I_S^-

Multiplying equation 2c by $-j/a$ and adding to equation 1, we obtain

$$V_M^+ = \frac{V_M}{2}(1 - j/a) \tag{24}$$

or by subtraction we obtain

$$V_M^- = \frac{V_M}{2}(1 + j/a) \tag{25}$$

From equations 3a and 24 we have

$$V_S^+ = \frac{V_M}{2}(1 + ja) \tag{26}$$

and from equations 4a and 25 we have

$$V_S^- = \frac{V_M}{2}(1 - ja) \tag{27}$$

Equations 13 and 14 now can be reconsidered together with equations 9, 10, 8a, and 23 and at the same time the sequence impedances Z_M^+, Z_M^-, Z_S^+ and Z_S^- can be included.

$$V_M = I_M^+ Z_M^+ + I_M^- Z_M^- \tag{13a}$$

$$V_M = j/a(I_M^+ Z_S^+ - I_M^- Z_S^-) \tag{14a}$$

To solve for I_M^- multiply equation 13a by Z_S^+/a^2 and equation 14a by $-j/aZ_M^+$

$$V_M \frac{Z_S^+}{a^2} = I_M^+ Z_M^+ \frac{Z_S^+}{a^2} + I_M^- Z_M^- \frac{Z_S^+}{a^2} \tag{13b}$$

$$-jV_M \frac{Z_M^+}{a} = I_M^+ \frac{Z_S^+}{a^2} Z_M^+ - I_M^- Z_M^+ \frac{Z_S^-}{a^2} \tag{14b}$$

If we subtract equation 14b from equation 13b

$$V_M\left(\frac{Z_S^+}{a^2} + j\frac{Z_M^+}{a}\right) = I_M^- \times \left(\frac{Z_M^- Z_S^+}{a^2} + \frac{Z_M^+ Z_S^-}{a^2}\right)$$

or

$$I_M^- = V_M\left[\frac{Z_S^+ + jaZ_M^+}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{28}$$

By applying equations 10 and 20

$$I_S^- = V_M\left[\frac{Z_M^+ - j\frac{Z_S^+}{a}}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{29}$$

To solve for I_M^+ multiply equation 13a by Z_S^-/a^2 and equation 14a by j/aZ_M^-.

$$V_M \frac{Z_S^-}{a^2} = I_M^+ Z_M^+ \frac{Z_S^-}{a^2} + I_M^- Z_M^- \frac{Z_S^-}{a^2} \tag{13c}$$

$$jV_M \frac{Z_M^-}{a} = -I_M^+ Z_S^+ \frac{Z_M^-}{a^2} + I_M^- Z_S^- \frac{Z_M^-}{a^2} \tag{14c}$$

If we subtract equation 14c from equation 13c,

$$V_M\left(\frac{Z_S^-}{a^2} - j\frac{Z_M^-}{a}\right) = I_M^+ \times \left(Z_M^+ \frac{Z_S^-}{a^2} + Z_M^- \frac{Z_S^+}{a^2}\right)$$

or

$$I_M^+ = V_M\left(\frac{Z_S^- - jaZ_M^-}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right) \tag{30}$$

By applying equations 9 and 19

$$I_S^+ = V_M\left[\frac{Z_M^- + j\frac{Z_S^-}{a}}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{31}$$

From equations 7, 28, and 30 we then obtain the general equation:

$$I_M = V_M\left[\frac{(Z_S^+ + Z_S^-) + ja(Z_M^+ - Z_M^-)}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{32}$$

and from equations 8, 29 and 31

$$I_S = V_M\left[\frac{(Z_M^+ + Z_M^-) - j/a(Z_S^+ - Z_S^-)}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{33}$$

The line current is the combined current of main and start phases.

$$I_L = I_M + I_S =$$

$$V_M\left[\frac{(Z_M^+ + Z_M^- + Z_S^+ + Z_S^-) + j\left(+ a Z_M^- + \frac{Z_S^-}{a} - \frac{Z_S^+}{a}\right)}{Z_M^+ Z_S^- + Z_M^- Z_S^+}\right] \tag{34}$$

Part II

These general equations will now be applied specifically to the single-phase motor.

The equivalent circuits of the M phase are shown in Figure 2. (See end of paper for definition of symbols.)

$$Z_{2M}^+ = \frac{R_2}{S} + jX_2 \tag{35}$$

secondary impedance to positive-sequence current.

By combining the magnetizing impedance jX_ϕ with the secondary impedance Z_{2M}^+ the "apparent secondary impedance" can be written

$$Z_2^{+\prime} = \frac{1}{\frac{1}{R_2/S + jX_2} + \frac{1}{jX_\phi}} = \frac{X_\phi^2 R_2/S}{(R_2/S)^2 + (X_\phi + X_2)^2} + j\frac{X_\phi\left(\frac{R_2}{S}\right)^2 + X_\phi X_2(X_\phi + X_2)}{(R_2/S)^2 + (X_\phi + X_2)^2} \tag{36}$$

or

$$Z_2^{+\prime} = R_2^{+\prime} + jX_2^{+\prime} \tag{36a}$$

where $R_2^{+\prime}$ and $jX_2^{+\prime}$ are apparent secondary positive-sequence resistance and apparent secondary positive-sequence reactance, respectively.

Similarly,

$$Z_{2M}^- = \frac{R_2}{2-S} + jX_2 \tag{37}$$

secondary impedance to negative-sequence current and

$$Z_2^{-\prime} = \frac{X_\phi^2 \frac{R_2}{2-S}}{\left(\frac{R_2}{2-S}\right)^2 + (X_\phi + X_2)^2} + j\frac{X_\phi\left(\frac{R_2}{2-S}\right)^2 + X_\phi X_2(X_\phi + X_2)}{\left(\frac{R_2}{2-S}\right)^2 + (X_\phi + X_2)^2} \tag{38}$$

$$Z_2^{-\prime} = R_2^{-\prime} + jX_2^{-\prime} \tag{38a}$$

where $R_2^{-\prime}$ and $X_2^{-\prime}$ are apparent secondary negative-sequence resistance and apparent secondary negative-sequence reactance, respectively.

The primary impedance of the M phase is

$$Z_{1M}^+ = Z_{1M}^- = R_{1M} + jX_{1M} \tag{39}$$

and of the S phase is

$$Z_{1S}^{+} = Z_{1S}^{-} = (R_{1S} + R_C) + j(X_{1S} - X_C) \quad (40)$$

in the case of a capacitor motor or

$$Z_{1S}^{+} = Z_{1S}^{-} = (R_{1S} + R_C) + jX_{1S} \quad (40a)$$

in the case of a resistance-split-phase motor having external resistance R_C.

The generalized impedances of the single-phase motor can now be written:

$$Z_M^{+} = (R_{1M} + R_2^{+}) + j(X_{1M} + X_2^{+}) \quad (41)$$

$$Z_M^{-} = (R_{1M} + R_2^{-}) + j(X_{1M} + X_2^{-}) \quad (42)$$

$$Z_S^{+} = (R_{1S} + R_C + a^2 R_2^{+}) + j(X_{1S} - X_C + a^2 X_2^{+}) \quad (43)$$

$$Z_S^{-} = (R_{1S} + R_C + a^2 R_2^{-}) + j(X_{1S} - X_C + a^2 X_2^{-}) \quad (44)$$

If we combine equation 30 with equations 41, 42, 43, 44,

$$I_M^{+} = V_M \times \left[\frac{(R_{1S} + R_C + a^2 R_2^{-}) + j(X_{1S} - X_C + a^2 X_2^{-}) - ja(R_{1M} + R_2^{-}) + a(X_{1M} + X_2^{-})}{\{(R_{1M} R_2^{+}) + j(X_{1M} + X_2^{+})\}\{(R_{1S} + R_C + a^2 R_2^{-}) + j(X_{1S} - X_C + a^2 X_2^{-})\} + \{(R_{1M} + R_2^{-}) + j(X_{1M} + X_2^{-})\}\{(R_{1S} + R_C + a^2 R_2^{+}) + j(X_{1S} - X_C + a^2 X_2^{+})\}} \right] \quad (45)$$

$$= V_M \times \left[\frac{\{(R_{1S} + R_C + a^2 R_2^{-}) + a(X_{1M} + X_2^{-})\} + j\{(X_{1S} - X_C + a^2 X_2^{-}) - a(R_{1M} + R_2^{+})\}}{\{\text{denominator of equation 45}\}} \right]$$

Likewise from equation 28,

$$I_M^{-} = V_M \times \left[\frac{\{(R_{1S} + R_C + a^2 R_2^{+}) - a(X_{1M} + X_2^{+})\} + j\{(X_{1S} - X_C + a^2 X_2^{+}) + a(R_M + R_2^{+})\}}{\{\text{denominator of equation 45}\}} \right] \quad (46)$$

and from equation 32,

$$I_M = V_M \times \left[\frac{\{2R_{1S} + 2R_C + a^2(R_2^{+\prime} + R_2^{-\prime})\} + j\{2X_{1S} - 2X_C + a^2(X_2^{+\prime} + X_2^{-\prime})\} + ja\{(R_2^{+\prime} - R_2^{-\prime}) + j(X_2^{+\prime} - X_2^{-\prime})\}}{\{\text{denominator of equation 45}\}} \right] \quad (47)$$

From equation 31,

$$I_S^{+} = V_M \times \left[\frac{\left\{(R_{1M} + R_2^{-}) - \frac{1}{a}(X_{1S} - X_C + a^2 X_2^{-})\right\} + j\left\{(X_{1M} + X_2^{-}) + \frac{1}{a}(R_{1S} + R_C + a^2 R_2^{-})\right\}}{\{\text{denominator of equation 45}\}} \right] \quad (48)$$

From equation 29,

$$I_S^{-} = V_M \times \left[\frac{\left\{(R_{1M} + R_2^{+}) + \frac{1}{a}(X_{1S} - X_C + a^2 X_2^{+})\right\} + j\left\{(X_{1M} + X_2^{+}) - \frac{1}{a}(R_{1S} + R_C + a^2 R_2^{+})\right\}}{\{\text{denominator of equation 45}\}} \right] \quad (49)$$

From equation 33,

$$I_S = V_M \times \left[\frac{\{(2R_{1M} + R_2^{+\prime} + R_2^{-\prime}) + j(2X_{1M} + X_2^{+\prime} + X_2^{-\prime})\} - \frac{j}{a}\{a^2(R_2^{+\prime} - R_2^{-\prime}) + ja^2(X_2^{+\prime} - X_2^{-\prime})\}}{\{\text{denominator of equation 45}\}} \right] \quad (50)$$

Output and Torque

In the case of a balanced two-phase motor, the *gross* rotor output is

$$WO_{2g} = 2|I_1|^2 \frac{R_2}{S}(1-S) \text{ watts} \quad (51)$$

Here only positive-sequence currents exist. The net rotor output is the gross output less friction and windage, iron loss, and load loss.

The motor torque in ounce feet is

$$T_{2\phi} = WO_{\text{net}} \times \frac{16 \times 33{,}000}{2\pi \times \text{rpm} \times 746} = \frac{112.7}{\text{rpm}} \times WO_{\text{net}} \quad (52)$$

The positive-sequence currents in the secondary winding produce torque in the direction of the phase rotation of these currents. When negative-sequence currents exist they produce a counter torque. As we are dealing with two balanced systems of two-phase currents we may consider the torques they produce as positive sequence and negative sequence.

Since

$$I_{2M}^{+} = \frac{jX_\phi}{R_2/S + j(X_\phi + X_2)} I_M^{+} \quad (53)$$

or

$$I_{2M}^{+} = \frac{X_\phi(X_\phi + X_2) + jX_\phi \frac{R_2}{S}}{(R_2/S)^2 + (X_\phi + X_2)^2} I_M^{+} \quad (53a)$$

and

$$I_{2M}^{-} = \frac{jX_\phi}{\frac{R_2}{2-S} + j(X_\phi + X_2)} I_M^{-} \quad (54)$$

or

$$I_{2M}^{-} = \frac{X_\phi(X_\phi + X_2) + jX_\phi \frac{R_2}{2-S}}{(R_2/2-S)^2 + (X_\phi + X_2)^2} I_M^{-} \quad (54a)$$

We now can write the gross power output in terms of the component secondary currents.

$$WO_{\text{gross}} = \left[|I_{2M}^{+}|^2 \left(\frac{R}{S}\right) + |I_{2S}^{+}|^2 \left(a^2 \frac{R_2}{S}\right) - |I_{2M}^{-}|^2 \left(\frac{R_2}{2-S}\right) - |I_{2S}^{-}|^2 \left(a^2 \frac{R_2}{2-S}\right) \right] (1-S) \quad (55)$$

From equations 9 and 10,

$$|I_{2S}^{+}| = \frac{|I_{2M}^{+}|}{a} \quad \text{and} \quad |I_{2S}^{-}| = \frac{|I_{1M}^{-}|}{a}$$

Substituting these in equation 55, we have

$$WO_{\text{gross}} = 2\left[|I_{2M}^{+}|^2 \frac{R_2}{S} - |I_{2M}^{-}|^2 \frac{R_2}{2-S} \right] \times (1-S) \text{ watts} \quad (55a)$$

Now observe that from equations 53a, 36, and 36a

$$|I_{2M}^{+}|^2 \frac{R_2}{S} = \frac{X_\phi^2 \frac{R_2}{S}}{(R_2/S)^2 + (X_\phi + X_2)^2} |I_M^{+}|^2 = R_2^{+1} |I_M^{+}|^2 \quad (56)$$

and from equations 54a, 38, and 38a,

$$|I_{2M}^{-}|^2 \frac{R_2}{2-S} = \frac{X_\phi^2 \frac{R_2}{2-S}}{\left(\frac{R_2}{2-S}\right)^2 + (X_\phi + X_2)^2} |I_M^{-}|^2 = R_2^{-\prime} |I_M^{-}|^2 \quad (57)$$

so that equation 55a reduces to the more convenient form:

$$WO_{\text{gross}} = 2[|I_M^{+}|^2 R_2^{+\prime} - |I_M^{-}|^2 R_2^{-\prime}] (1-S) \text{ watts} \quad (55b)$$

Efficiency and Power Factor

By adding I_M (equation 47) and I_S (equation 50) the line current I_L can be obtained.

The "inphase" component of I_L multiplied by the line voltage (V_M) gives us the watts input, while $I_L \times V_M$ gives us the volt-ampere input.

$$\text{Power factor} = \frac{\text{watts input}}{\text{volt-amperes input}} \quad (58)$$

After subtracting the rotational losses (friction and windage, iron loss and load loss) from equation 55b, we have the net output watts, WO net

$$\text{Efficiency} = \frac{WO \text{ net}}{\text{watts input}} \quad (59)$$

Part III. Some Cases of Particular Interest

Exact Two-phase Motor Performance

A single-phase motor can be made to have phase balance and perform as a two-phase motor if the negative-sequence components of current can be made to vanish. From equations 46 and 49 we can write

$$0 = |(R_{1S} + R_C + a^2 R_2^{+}) - a(X_{1M} + X_2^{+})| + j|(X_{1S} - X_C + a^2 X_2^{+}) + a(R_{1M} + R_2^{+})| \quad (46a)$$

$$0 = \left\{(R_{1M} + R_2^{+}) + \frac{1}{a}(X_{1S} - X_C + a^2 X_2^{+})\right\} + j\left\{(X_{1M} + X_2^{+}) - \frac{1}{a}(R_{1S} + R_C + a^2 R_2^{+})\right\} \quad (49a)$$

By equating the real and imaginary components to zero separately, in each case

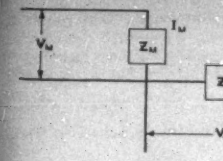

Figure 1

we can write the required condition for balance,

$$\begin{cases} R_C = a(X_{1M} + X_S^{+\prime}) - (R_{1S} + a^2 R_S^{+\prime}) & (60) \\ X_C = a(R_{1M} + R_S^{+\prime}) + (X_{1S} + a^2 X_S^{+\prime}) & (61) \end{cases}$$

This relationship holds for a particular value of speed as $X_S^{+\prime}$ and $R_S^{+\prime}$ are functions of slip. The condition cannot always be met as ($R_{1S} + a^2 R_S^{+\prime}$) may be greater than $a(X_{1M} + X_S^{+\prime})$ which would require R_C to be negative. Completely eliminating the negative-sequence currents does not necessarily mean higher efficiency as additional losses may be incurred if R_C must be much greater than a small percentage of R_{1S}.

Start Phase Disconnected

In the usual capacitor-start or resistance-split-phase motor the start phase is disconnected by centrifugal switch or relay action at one half to eight tenths of synchronous rpm. Of course, I_S becomes zero, but its symmetrical components still exist.

We can consider

$$\lim_{R_C \longrightarrow \infty}$$

If ∞ is substituted for R_C in equations 45 and 46, they will take the indeterminate form ∞/∞. By differentiating numerators and denominators with respect to R_C and again substituting ∞ for R_C we have in the limit,

$$I_M^+ = V_M \frac{1}{[(R_{1M} + R_S^{+\prime}) + j(X_{1M} + X_S^{+\prime})] + [(R_{1M} + R_S^{-\prime}) + j(X_{1M} + X_S^{-\prime})]} \quad (62)$$

$$= V_M \frac{1}{(2R_{1M} + R_S^{+\prime} + R_S^{-\prime}) + j(2X_{1M} + X_S^{+\prime} + X_S^{-\prime})}$$

and

$$I_M^- = V_M \frac{1}{(2R_{1M} + R_S^{+\prime} + R_S^{-\prime}) + j(2X_{1M} + X_S^{+\prime} + X_S^{-\prime})} \quad (63)$$

Note that $I_M^+ = I_M^-$

so that

$$I_M = I_M^+ + I_M^- \quad (7)$$

or

$I_M = 2I_M^+ = 2I_M^-$ for this case

or

$$I_M^+ = \frac{I_M}{2} = I_M^- \quad (64)$$

Therefore,

$$I_M = \frac{V_M}{\left(R_{1M} + \frac{R_S^{+\prime} + R_S^{-\prime}}{2}\right) + j\left(X_{1M} + \frac{X_S^{+\prime} + X_S^{-\prime}}{2}\right)} \quad (65)$$

or

$$I_M = V_M \frac{\left(R_{1M} + \frac{R_S^{+\prime} + R_S^{-\prime}}{2}\right) - j\left(X_{1M} + \frac{X_S^{+\prime} + X_S^{-\prime}}{2}\right)}{\left(R_{1M} + \frac{R_S^{+\prime} + R_S^{-\prime}}{2}\right)^2 + \left(X_{1M} + \frac{X_S^{+\prime} + X_S^{-\prime}}{2}\right)^2} \quad (65a)$$

From equations 64 and 55b we can now obtain the output for this condition

$$WO_{gross} = 2\left[\left|\frac{I_M}{2}\right|^2 R_S^{+\prime} - \left|\frac{I_M}{2}\right|^2 R_S^{-\prime}\right](1-S)$$

$$= |I_M|^2 \left(\frac{R_S^{+\prime} - R_S^{-\prime}}{2}\right)(1-S) \text{ watts} \quad (66)$$

At standstill ($S = 1$) $R_S^{+\prime} = R_S^{-\prime} = R_S$ since

$$\frac{R_S}{S} = \frac{R_S}{2-S}$$

Equation 66 shows that the output is zero in actual as well as synchronous watts. As the synchronous-watts output is zero there naturally can be no torque.

The standstill current input becomes

$$_{SS}I_M = \frac{V_M}{(R_{1M} + R_S) + j(X_{1M} + X_S)} \quad (67)$$

At synchronous speed ($S = 0$)

Examining equation 36 we find that $Z_S^{+\prime}$ takes the indeterminate form $\infty/\infty + j\infty/\infty$. When numerators and denominators are differentiated with respect to R_S/S, and ∞ is again substituted for R_S/S, the equation becomes:

$$_sZ_S^{+\prime} = jX_\phi \quad _sZ_S^{+\prime} = 0 \quad _sZ_S^{+\prime} = jX_\phi \quad (68)$$

while

$$_sZ_S^{-\prime} = \frac{X_\phi^2 \frac{R_S}{2}}{\frac{R_S^2}{4} + (X_\phi + X_S)^2} + j\frac{X_\phi \frac{R_S^2}{4} + X_\phi X_S(X_\phi + X_S)}{\frac{R_S^2}{4} + (X_\phi + X_S)^2} \quad (69)$$

From equation 65a we derive

$$I_M = V_M \frac{\left\{R_{1M} + \frac{X_\phi^2 \frac{R_S}{4}}{R_S^2/4 + (X_\phi + X_S)^2}\right\} - j\left\{X_{1M} + \frac{X_\phi R_S^2/4}{R_S^2/4 + (X_\phi + X_S)^2}\right\}}{\left\{R_{1M} + \frac{X_\phi R_S^2/4}{R_S^2/4 + (X_\phi + X_S)^2}\right\}^2 + j\left\{X_{1M} + \frac{X_\phi}{2}\left[1 + \frac{R_S^2/4 + X_S(X_\phi + X_S)}{R_S^2/4 + (X_\phi + X_S)^2}\right]\right\}} \quad (70)$$

Voltage Across Start Phase

Frequently there is need of knowing the voltage across the starting winding proper to make control applications either on the motor or for auxiliary apparatus.

Case of Capacitor Motor

$$V_{\phi S} = V_M - E_C \quad (71)$$

where

$$E_C = I_S(R_C - jX_C) \quad (72)$$

I_S is calculated from equation 50.

Case of Capacitor-Start or Resistance-Split-Phase Motor After the Starting Switch Opens the Start Phase

If

$$\lim_{R_C \longrightarrow \infty}$$

equations 48and 49 take the indeterminate form ∞/∞, but by differentiation it will be found that

$$I_S^+ = V_M \frac{j/a}{(R_{1M} + R_S^{+\prime}) + j(X_{1M} + X_S^{+\prime}) + (R_{1M} + R_S^{-\prime}) + j(X_{1M} + X_S^{-\prime})} \quad (73)$$

$$I_S^+ = V_M \frac{j/a}{(2R_{1M} + R_S^{+\prime} + R_S^{-\prime}) + j(2X_{1M} + X_S^{+\prime} + X_S^{-\prime}} \quad (73a)$$

and

$$I_S^- = V_M \frac{-j/a}{(2R_{1M} + R_S^{+\prime} + R_S^{-\prime}) + j(2X_{1M} + X_S^{+\prime} + X_S^{-\prime})} \quad (74)$$

Note that $I_S^+ = -I_S^-$ and $I_S = I_S^+ + I_S^- = 0$

$$V_{S\phi}^+ = I_S^+ a^2 Z_S^{+\prime} \quad (75)$$

$$V_{S\phi}^- = I_S^- a^2 Z_S^{-\prime} = -I_S^+ a^2 Z_S^{-\prime} \quad (76)$$

If we add

$$V_{S\phi} = V_{S\phi}^+ + V_{S\phi}^- = I_S^+ a^2 (Z_S^{+\prime} - Z_S^{-\prime}) = V_M \frac{j/a[a^2(R_S^{+\prime} - R_S^{-\prime}) + ja^2 \times}{(2R_{1M} + R_S^{+\prime} + R_S^{-\prime}) + j(2X_{1M} + (X_S^{+\prime} - X_S^{-\prime})} \quad (77)$$

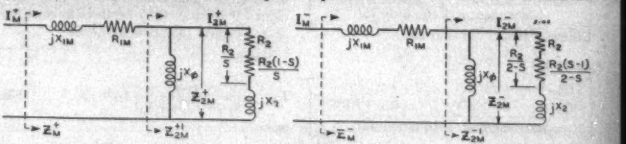

Figure 2

$$V_{s\phi} = V_M a \frac{-(Z_s^{+\prime} - Z_s^{-\prime}) + j(R_s^{+\prime} - R_s^{-\prime})}{(2R_{1M} + R_s^{+\prime} + R_s^{-\prime}) + j(2X_{1M} + X_s^{+\prime} + X_s^{-\prime})} \quad (77a)$$

Observe that at standstill, when

$X_s^{+\prime} = X_s^{-\prime} = X_s'$ and $R_s^{+\prime} = R_s^{-\prime} = R_s'$

$V_{s\phi}$ becomes zero

STARTING TORQUE

In routine design work the calculation of starting torque, together with the capacitor voltage or starting current, is of particular importance as the running performance can often be proportioned accurately from existing similar tested designs.

$$\text{Let } I_M = A + jB = \frac{V_M}{Z_M} \quad (78)$$

$$\text{Let } I_S = C + jD = \frac{V_M}{Z_S} \quad (79)$$

Since

$R_s^{+\prime} = R_s^{-\prime} = R_s'$ and $X_s^{+\prime} = X_s^{-\prime} = X_s'$

$Z_S^+ = Z_S^- = Z_S$ and $Z_M^+ = Z_M^- = Z_M$

Equation 30 becomes

$$I_M^+ = V_M \frac{Z_S - jaZ_M}{2Z_SZ_M} = \frac{V_M}{2Z_M} - ja\frac{V_M}{2Z_S} \quad (80)$$

or

$$I_M^+ = \frac{I_M}{2} - ja\frac{I_S}{2} \quad (80a)$$

and equation 28 becomes

$$I_M^- = V_M \frac{Z_S + jaZ_M}{2Z_MZ_S} = \frac{V_M}{2Z_M} + ja\frac{V_M}{2Z_S} \quad (81)$$

or

$$I_M^- = \frac{I_M}{2} + ja\frac{I_S}{2} \quad (81a)$$

Now if we use equations 78 and 79 in equation 80a,

$$I_M^+ = \left(\frac{A}{2} + j\frac{B}{2}\right) - ja\left(\frac{C}{2} + j\frac{D}{2}\right)$$

$$= \left(\frac{A}{2} + a\frac{D}{2}\right) + j\left(\frac{B}{2} - a\frac{C}{2}\right) \quad (82)$$

$$|I_M^+|^2 = \frac{(A+aD)^2}{4} + \frac{(B-aC)^2}{4} \quad (83)$$

Similarly if we use equations 78 and 79 in equation 81a,

$$I_M^- = \left(\frac{A}{2} + j\frac{B}{2}\right) + ja\left(\frac{C}{2} + j\frac{D}{2}\right)$$

$$= \left(\frac{A}{2} - a\frac{D}{2}\right) + j\left(\frac{B}{2} + a\frac{C}{2}\right) \quad (84)$$

$$|I_M^-|^2 = \frac{(A-aD)^2}{4} + \frac{(B+aC)^2}{4} \quad (85)$$

and

$$|I_M^+|^2 - |I_M^-|^2 = a(AD - BC) \quad (86)$$

to obtain the theoretical torque we will combine equations 52, 55b, and 85 and

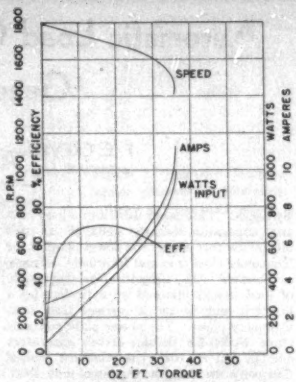

Figure 3. Calculated one-quarter-horsepower-motor performance data

at the same time eliminate the motor speed by the following relationship

rpm = $(1-S)$ synchronous rpm

so that

$$T = \frac{112.7}{(1-S)\text{synchronous}} \times 2R_s'a(AD-BC)(1-S) \quad (87)$$

This is an indeterminate of the form 0/0 for $S = 1$, but

$$\lim_{S \to 1} \frac{1-S}{1-S} = 1$$

$$T = \frac{225.4}{\text{synchronous}} R_s'a(AD-BC) \text{ ounce-feet} \quad (87a)$$

For the usual capacitor motor:

A is positive.
B is negative.
C is positive.
D is positive.

For the usual resistance-split-phase motor:

A is positive.
B is negative.
C is positive.
D is negative.

This theoretical value of standstill torque must be modified by an empirical factor to take account of friction, iron loss, and tooth-locking effects in a practical design.

Conclusions

The author has endeavored to demonstrate the versatility of the symmetrical-component method in the solution of single-phase induction motors. The theory is "continuous" mathematically in that special cases are set up simply by allowing some parameter to be zero or infinity to fit the physical aspects of the problem.

The derivations are general enough so that, if R_s is not the same for the low-frequency positive-sequence rotor currents as it is for the higher-frequency negative-sequence rotor currents, allowances can be made in the calculations.

Nomenclature

V_M = main-phase rms volts
V_S = start-phase rms volts
V_M^+ = positive-sequence component of V_M
V_M^- = negative-sequence component of V_M
V_S^+ = positive-sequence component of V_S
V_S^- = negative-sequence component of V_S
I_M = main-phase rms amperes
I_S = start-phase rms amperes
I_M^+ = positive-sequence component of I_M
I_M^- = negative-sequence component of I_M
I_S^+ = positive-sequence component of I_S
I_S^- = negative-sequence component of I_S
a = $\frac{\text{effective conductors of } S \text{ phase}}{\text{effective conductors of } M \text{ phase}}$
s = per-unit slip
I_{1M}^+ = positive-sequence component of M-phase secondary current referred to primary current
I_{1M}^- = negative-sequence component of M-phase secondary current referred to primary current
I_{1S}^+ = positive-sequence component of S-phase secondary current referred to primary current
I_{1S}^- = negative-sequence component of S-phase secondary current referred to primary current
Z_M^+ = total positive-sequence impedance of M phase
Z_M^- = total negative-sequence impedance of M phase
Z_S^+ = total positive-sequence impedance of S phase
Z_S^- = total negative-sequence impedance of S phase
X_{1M} = reactance of M-phase primary winding
R_{1M} = resistance of M-phase primary winding
R_s = equivalent M-phase secondary resistance referred to primary winding
X_s = equivalent M-phase secondary reactance referred to primary winding
X_ϕ = equivalent M-phase mutual or magnetizing reactance
$Z_s^+ = \frac{R_s}{S} + jX_s$ = positive-sequence secondary impedance of M phase referred to primary winding
$Z_s^- = \frac{R_s}{2-S} + jX_s$ = negative-sequence secondary impedance of M phase referred to primary winding
$R_s^{+\prime}$ = apparent positive-sequence M-phase secondary resistance
$= \frac{X_\phi^2 R_s/s}{(R_s/s)^2 + (X_\phi + X_s)^2}$
$R_s^{-\prime}$ = apparent negative-sequence M-phase secondary resistance
$= \frac{X_\phi^2 \frac{R_s}{2-S}}{\left(\frac{R_s}{2-S}\right)^2 + (X_\phi + X_s)^2}$

$X_s^{+'}$ = apparent positive-sequence M-phase secondary reactance

$$= \frac{X_\phi(R_3/s)^2 + X_\phi X_3(X_\phi + X_3)}{(R_3/s)^2 + (X_\phi + X_3)^2}$$

$X_s^{-'}$ = apparent negative-sequence M-phase secondary reactance

$$= \frac{X_\phi(R_3/(2-S))^2 + X_\phi X_3(X_\phi + X_3)}{(R_3/(2-S))^2 + (X_\phi + X_3)^2}$$

$Z_s^{+'} = R_s^{+'} + jX_s^{+'}$ Z_s' = standstill apparent secondary impedance

$Z_s^{-'} = R_s^{-'} + jX_s^{-'}$ R_s' = standstill apparent secondary resistance

X_s' = standstill apparent secondary reactance

$Z_{1M}^{+} = Z_{1M}^{-} = R_{1M} + jX_{1M}$ = primary impedance

R_{1S} = resistance of S-phase primary winding

X_{1S} = reactance of S-phase primary winding

X_C = capacitor reactance

R_C = capacitor resistance or other external resistance in S phase

$T_{2\phi}$ = two-phase-motor torque, ounce-feet

Synch = synchronous rpm

WO = gross watts output of rotor

T = single-phase-motor torque, ounce-feet

E_C = capacitor voltage

$V_{S\phi}$ = voltage across S-phase winding

Sample Calculation

One-quarter horsepower, four pole, 110 volts 60 cycle; capacitor-start motor

Constants

$R_3 = 2.48$ (25 degrees centigrade)

$R_1 = 1.63$ (25 degrees centigrade)

$X_1 = 2.47$, $X_3 = 2.44$, $X_\phi = 67.28$

Friction loss = $W_f = 16.5$ watts

Iron loss = $W_i = 23.5$ watts

$S = 0.038$

Rpm = $(1 - 0.038)\ 1{,}800 = 1{,}732$

$R_3/s = 65.25$ $R_3/1-s = 1.264$

$$R_s^{+'} = \frac{67.28^2 \times 65.25}{65.25^2 + (67.28 + 2.44)^2} = 32.40$$

$$R_s^{-'} = \frac{67.28^2 \times 1.264}{1.264^2 + (67.28 + 2.44)^2} = 1.177$$

$$X_s^{+'} = \frac{67.28 \times 65.25^2 + 67.28 \times 2.44(67.28 + 2.44)}{65.25^2 + (67.28 + 2.44)^2} = 32.70$$

$$X_s^{-'} = \frac{67.28 \times 1.264^2 + 67.28 \times 2.44(67.28 + 2.44)}{1.264^2 + (67.28 + 2.44)^2} = 2.375$$

$$I_M = 110 \left[\left(1.63 + \frac{32.40 + 1.18}{2} \right) - j\left(2.47 + \frac{32.70 + 2.38}{2} \right) \right] \Bigg/ \left[\left(1.63 + \frac{32.40 + 1.18}{2} \right)^2 + \left(2.47 + \frac{32.70 + 2.38}{2} \right)^2 \right]$$

$$= 110 \left[\frac{18.42 - j20.01}{339.5 + 441} \right]$$

$$= 2.595 - j2.963 \quad |I_M| = 3.94$$

$$|I_M|^2 = 15.51$$

$$WO_{gross} = 15.51(1 - 0.038)\left(\frac{32.40 - 1.18}{2}\right)$$

$$= 15.51 \times 0.962 \times 15.61 = 233.2 \text{ watts}$$

$WO_{net} = 233.2 - 16.5 - 23.5 = 193.2$

Torque = $(112.7/1732) \times 193.2 = 12.55$ ounce-feet

Watts input = $110 \times 2.595 = 285.5$

Eff = $193.2/285.5 = 0.695$

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Automatic Load Control for Turbine Generators

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Synopsis: This paper describes a load-control apparatus recently installed on two 20,000-kw turbines at the power plant of the Tennessee Coal Iron and Railroad Company at Fairfield, Ala., to reduce the magnitude of load swings imposed on a tie line by a hot-strip mill in the Tennessee Coal Iron Company plant. The power plant contains three 20,000-kw turbine-driven generators and is tied in with the Alabama Power Company to furnish the steel-mill load. Previous to the installation of the equipment herein described, the three 20,000-kw turbine generators have carried load under control of their speed governors and the variations in strip-mill load which are about 20,000 kw were imposed upon the Alabama Power Company tie line causing objectionable disturbances on the connecting power system. It was desired to develop a means of imposing all or part of the strip-mill load on the Tennessee Coal Iron and Railroad Company turbine generators to reduce these disturbances. Several methods were considered, and the one selected was based upon a static watt-measuring circuit, the output of which is an Amplidyne generator. The Amplidyne in turn operates the pilot motor of an hydraulic (oil) relay at the turbine to control the steam admission valves.

GIVEN a base load and a variable load and a variable supply of steam for either one of two prime movers, the regulator is to cause the prime movers to take

(*a*). A base load, adjustable from 1/20th rated load to rated load.

(*b*). In addition to condition *a* any desired percentage of the variable load from 0 to 100 per cent.

(*c*). Both the base load and the variable load are to be reduced automatically as the steam pressure falls below a nominal pressure.

(*d*). The variable load is to be divided in any desired ratio between the two prime movers by simple adjustment.

(*e*). The variable load may have instantaneous rates of change as high as 5,000 kw per second with average rates of approximately 2,000 kw per second during load increase and decrease. The variable load peaks are approximately 20,000 kw in magnitude of 20 to 100 seconds duration with intervals of light load of about the same duration. It is desired to minimize the variation of load on the tie line insofar as practical.

In addition, the governing system is desired to have the following features:

(*a*). A definite limit on turbine speed must at all times be in opeation.

(*b*). It must be possible for operating either or both turbines on their speed governors.

(*c*). It must be possible to change easily from power to speed governing and vice versa.

(*d*). The power-governing system must be fast in response and be stable in operation.

Fundamentals of Electric-Power-Measuring Circuit

As balanced three-phase loads are to be governed a single-phase power-measuring circuit suffices to control the operation. Also, as the machines operate at constant voltage if is sufficient to control the unity power factor or kilowatt component of generator current.

The essentials of the power-measuring circuit are shown in Figure 1.

The Amplidyne generator has been described adequately elsewhere.[1–4] For pres-

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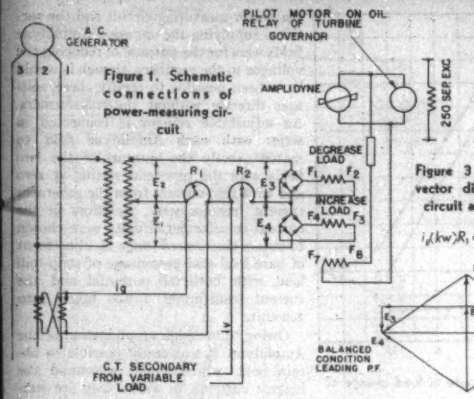


Figure 1. Schematic connections of power-measuring circuit

Figure 2 (right). Voltage vector diagram of measuring circuit at zero load setting

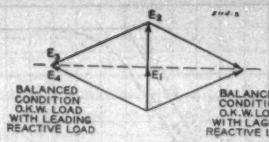
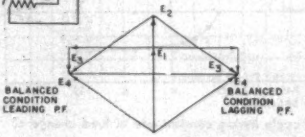


Figure 3 (below). Voltage vector diagram of measuring circuit at fixed load setting

$$i_g(kw)R_1 = \frac{E_1+E_2}{2} - E_2 = \frac{E_1-E_2}{2}$$



ent purposes it is sufficient to say that the Amplidyne output voltage is extremely sensitive to a difference between the ampere turns of the fields F_1F_2 and F_3F_4 which are excited in opposite directions (so as to oppose each other) from selenium rectifiers as shown. The Amplidyne output voltage will be zero, and the motor which operates the hydraulic governing mechanism will be at rest only when the currents in these two fields are equal and opposite. As the two fields have the same number of turns and the same resistance this balance occurs only when the alternating voltages at the rectifier inputs are equal in magnitude. Assume for the moment that the adjustable voltage tap is set so that $E_1 = E_2$ and that $i_v = 0$ in Figure 1. Then $|E_3| = |E_4|$ only when the kilowatts or unity-power-factor component of current i_g is zero regardless of the reactive component of current i_v. Figure 2 illustrates this.

If the adjustable tap is set so that E_1 is greater than E_2 while the sum of E_1 and E_2 remains constant, the balanced condition when $|E_3| = |E_4|$ will occur only when the kilowatt load on the turbine generator is constant so that the inphase component of $i_g \times R_1 = (E_1 - E_2)/2$.

Figure 3 illustrates this condition at various power factors on the generator.

From the foregoing it is evident that for a fixed value of R_1 and with R_2 set at zero the load on the turbine when the Amplidyne output voltage is zero is proportional to the voltage between the mid-tap of the potential-transformer secondary winding and the position of the adjustable tap. The adjustable tap then is used as the base-load setting of the generator.

If R_2 is not zero the load on the turbine when $|E_3| = |E_4|$ will be such that

$$i_g \times R_1 = \frac{E_1 - E_2}{2} + i_v \times R_2$$

where

i_g = unity-power-factor component of generator current

i_v = unity-power-factor component of variable load current

By setting the adjustable voltage tap the base load of the turbine is fixed at any desired value and by setting the value of R_2 any desired percentage of the variable load up to 100 per cent may be carried.

In order to decrease both the base-load setting and the percentage of the variable load taken by the turbine the value of R_1 is increased automatically as the steam pressure decreases below a set value.

In Figure 1 field F_7F_8 of the Amplidyne is connected as an inverse feedback of the Amplidyne output into its input. This results in a more linear relationship between the Amplidyne input and output than would be the case without this connection and gives a means of adjusting rate of operation of the governing mechanism as a function of the deviation between the load on the turbine and the load setting of the regulator

Electrical Connections

A schematic diagram of the electric-system connections and of the power regulators is shown in Figure 4. In order to make the kilowatt component of turbogenerator current in phase with the voltage to the regulator circuit it was necessary to add the currents of phases 1 and 2 when using potential 1–2. This was done with current transformers in the secondary circuits of existing current transformers. Owing to existence of a wye–delta transformer bank between the generator and the strip-mill circuit a single current-transformer in phase 1 gave the required phase relationship of strip-mill current with respect to the regulator voltage. This latter current is transmitted approximately 4,000 feet to the control room of the power plant. As it was desired to shift the variable load between the two power-regulated generators without disturbing the percentage of strip-mill load carried an adjustable-ratio current transformer was used to divide the strip-mill current between the two regulators in any ratio so that the sum of the currents to the two regulators remains in constant ratio to the strip-mill current. A "variac" was used as a means of adjusting the relationship of voltages E_1 and E_2, and its setting determined the base load. The transformers used between

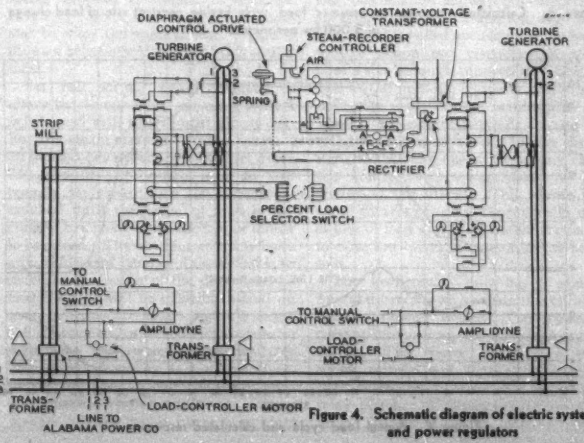


Figure 4. Schematic diagram of electric system and power regulators

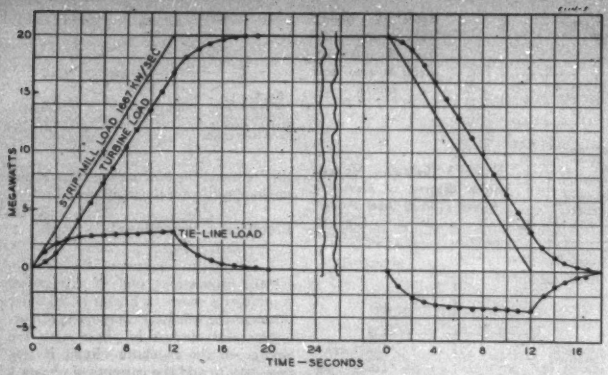


Figure 5. Calculated response to assumed load cycle having constant rate of load change of 1,667 kw per second

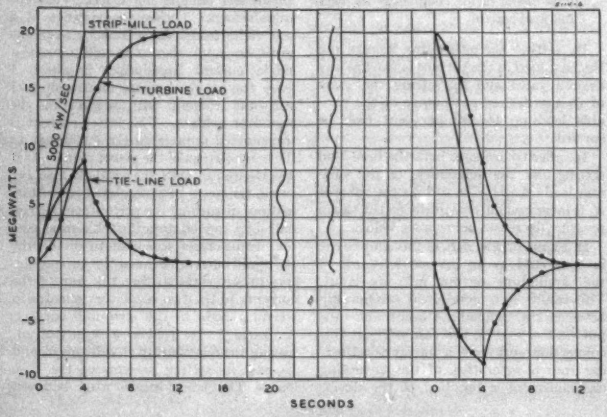


Figure 6. Calculated response to assumed load cycle having constant rate of load change of 5,000 kw per second

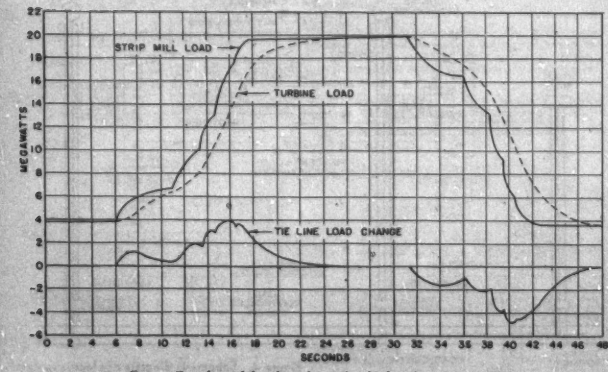


Figure 7. Actual load cycle and calculated response

the power-measuring circuit and the rectifiers supplying the opposing Amplidyne fields were for the purpose of reducing the voltages to the rectifiers, though it would have been possible to rectify these voltages directly without the transformers. An adjustable resistor is connected in series with each Amplidyne field to match exactly the currents to the two fields with the base-load setting at zero and with zero current from the generator current transformers. Resistors in the current-transformer circuits were chosen to obtain the desired range of adjustment of base load and percentage of strip-mill load, with both the potential and the current transformer ratios taken into account.

Owing to the high amplification of the Amplidyne, it was easily possible to obtain fields which would withstand the highest currents to which they are subjected (which vary with power factor) and at the same time to obtain more than adequate sensitivity to power variation.

Sensitivity

The Amplidyne voltage output per kilowatt difference between regulator setting and turbogenerator load may be adjusted by means of the variable resistor in series with field F_7F_8 of the Amplidyne. Without this feedback it requires approximately 2,000 kw deviation between regulator setting and generator load to run the pilot motor through full travel in four seconds. In practice it was necessary to adjust the feedback to obtain stable operation so that the deviation required to cause the generator to increase its load at a rate of 5,000 kw per second was approximately 6,500 kw. Final adjustment with which the operation data were taken was with 10,000 kw deviation required to give a rate of 5,000 kw per second. With this adjustment the kilowatt deviation to cause the Amplidyne voltage necessary just to rotate the pilot motor against friction was approximately 200 kw, so that with a setting of 20,000 kw the power is held within plus or minus one per cent during steady state.

Response

All of the regulating elements are relatively fast in response in comparison with the time required to operate the pilot motor of the governing mechanism. This time together with the kilowatts deviation required to obtain a given pilot-motor speed determines the response of the system. Also, it will be shown that these factors, together with the rate of change of the variable load and the percentage of the variable load carried by the Tennessee Coal Iron and Railroad Company turbines, determine the effectiveness of the regulating system

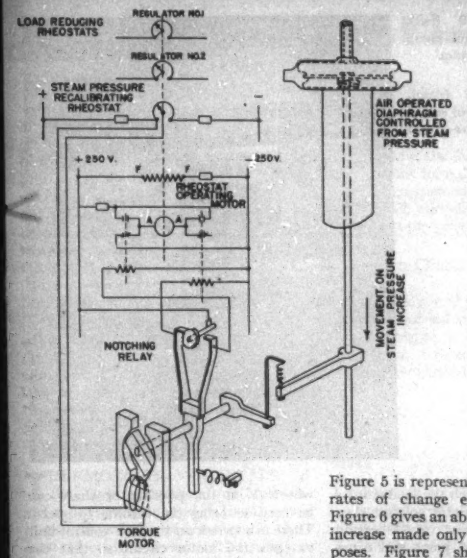


Figure 8 (left). Schematic diagram of steam-pressure-regulating system

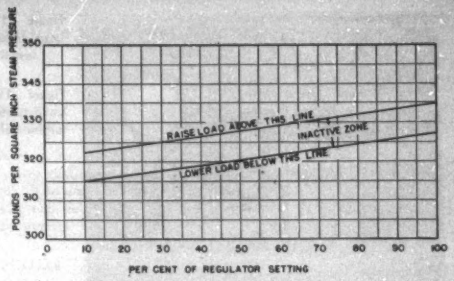


Figure 9 (above). Characteristics of steam-pressure regulator

in minimizing the variation in tie-line load.

Let

Tkw = kilowatt load on turbine generator
Lkw = kilowatt setting of load regulator
$P = \frac{d}{dt}$
K = proportionality constant between rate of change of turbine load and deviation of load from regulator setting

Then

$$KP\ Tkw = (Lkw - Tkw)$$
$$Tkw = \frac{Lkw}{KP+1}$$

With

Tkw = 5,000 kw per second
$Lkw - Tkw$ = 10,000 kw
$K = 2$

The solution for unit change of Lkw (caused by a change of strip-mill load) is

$$Tkw = Lkw(1 - \epsilon^{-1/t})$$

If now Lkw is varying at a constant rate R it can be shown by the superposition theorem that (if we assume $Lkw = 0$ when $T = 0$)

$$Tkw = R(t - 2 + 2\epsilon^{-1/t})$$

With an assumed load cycle as in Figure 5 the response and the variation in tie-line load were calculated as shown in this same figure from this formula and the preceding one. A similar curve is shown in Figure 6 for a rate of strip-mill-load increase of 5,000 kw per second. Figure 5 is representative of the average rates of change encountered, whereas Figure 6 gives an abnormally high rate of increase made only for comparison purposes. Figure 7 shows an actual strip-mill-load peak taken from a load chart. The calculated turbine load based upon 100-per-cent pickup of strip-mill load and the load on the tie line are calculated and shown in this same figure.

Means of Reducing Loads Upon Decrease in Steam Pressure

The means of reducing both the base load and the variable load in equal percentages upon reduction in steam pressure was to increase resistance R_1, Figure 1. A Bailey Meter Company pilot valve was used to give a definite motion of a spring opposing the action of a torque motor to control a motor-operated rheostat to vary the value of R_1. Figure 8 shows a schematic diagram of this equipment.

For full normal steam pressure or above the torque-motor notching system is balanced with the rheostat all cut out. For any steam pressure within a range of 30 pounds per square inch, that is, from 340 pounds per square inch to 310 pounds per square inch the rheostat is notched until the value of load is decreased to a point where the torque motor is balanced. The notching contacts have adjustable dead band, and the action is to notch to the center of the dead band so that the load will be reduced to hold an average steam pressure. Figure 9 shows the characteristics of the steam-pressure regulator. This steam-pressure regulator is intended primarily as a means of reducing the loads to keep the steam pressure above a certain minimum. It can operate continuously in range to regulate steam pressure. Normally, however, it was intended that the load settings would be such that full steam pressure could be maintained, with the steam pressure above the range of the pressure regulator. Figure 10 shows the control panels for the two turbine generators. The panel at the left is for one generator. The middle panel contains the variable-ratio current transformer by means of which the strip-mill load may be divided between the two machines. The third panel from the left duplicates the first panel for the other turbine. On the extreme right is the steam-pressure controller. The base-load adjustment, regulator on-and-off switch, and the percentage of strip-mill load all are operated from the front of these panels.

Turbine Valve Control

The schematic arrangement of the turbine control is shown on Figure 11. The load-control relay unit and the initial pressure regulator were added to the original governor unit and connected with a telescope joint in the governor connection so that, while the load control is used, the speed governor can be run to its full-load position and act as a pre-emergency governor. In this condition the telescope joint is pulled open and the the load-control piston rod controls the main pilot valve through connection F and E. The initial pressure-regulator piston rod can pick up through connection D. These three connections (F, D, and E) will transmit motion only in one direction, so that any one of them may close the control valves regardless of the setting of the others. This allows the speed governor to close the valves in case of loss of load and the pressure regulator to close the valves in case of loss of pressure.

The load-control unit has a shunt-wound d-c motor with constant excitation from a 250-volt source. The armature current comes from the Amplidyne generator. The motor operates a lead screw raising and lowering the relay pilot valve and so raises and lowers the relay piston. A friction clutch is provided in the drive so that no limit

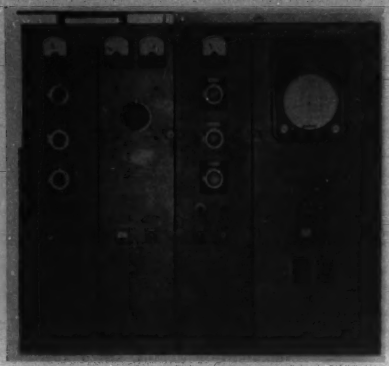


Figure 10 (left). Load-control panel installation

Figure 12 (right). Load-control unit of turbine-valve control

switches are necessary and limit-switch dead band is eliminated. An oil spray lubricates the clutch to prevent wear in case the motor runs long periods of time at the end of the travel. Motion of the relay piston is transmitted to the main pilot valve and so to the main hydraulic piston, opening and closing the control valves through the rack and pinion and the cams.

The pressure regulator consists of a spring-loaded bellows which operates a relay pilot valve and controls an oil piston. The spring plug may be adjusted by handwheel *C* so that the regulator will close the valves at pressures from 275 to 350 pounds per square inch. A stop is provided on both the load control and the pressure regulator so that they cannot close the turbine valves beyond the no-load steam-flow point and cause overheating of the turbine by motoring. The speed governor always can close the valves completely on a rise in speed to the pre-emergency setting. However, an adjustment is provided on the load-control piston rod so that when the turbine is shut down the control valves can be closed completely, and then handwheel *A* on the pilot-motor shaft can be used to bring the turbine to speed. There is a switch on the load-control unit to open the motor circuit so that the handwheel can be used without danger of the motor starting up. The load-control and initial pressure regulator are enclosed in a small case mounted on the turbine base adjacent to the front pedestal. Figure 12 is a view of the installation.

The rates of load change imposed by this regulator will exceed what normally is considered good practice from the standpoint of economy and maintenance, but the 20,000-kw turbines at Tennessee Coal Iron and Railroad Company are low pressure and temperature and of a rugged design with a relatively short span between bearings; they should be able to withstand the quick load changes without undue distress. There most likely will be some increased maintenance necessary on machines subjected to continuous quick load changes, especially on the control mechanism, valves, cams, rack, and pinion, and so on.

The actual performance of the load-control unit was as good as anticipated. Load changes were made quickly, positively, and without hunting.

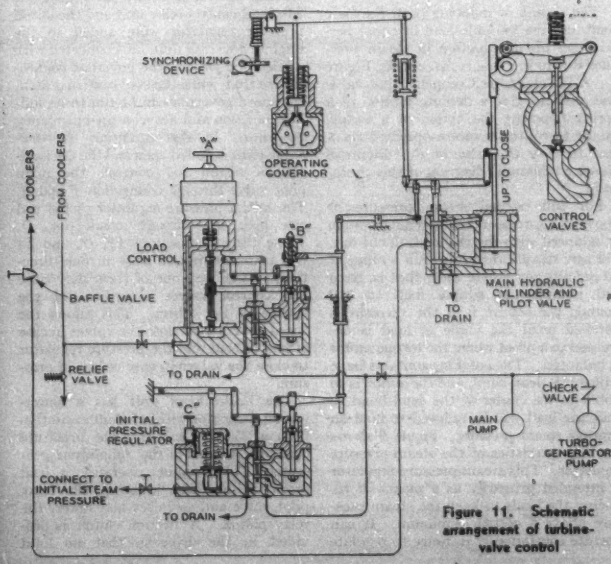


Figure 11. Schematic arrangement of turbine-valve control

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Tapered-Thickness Bimetal

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Synopsis: The most important properties of thermostatic bimetal strips of uniformly tapered width or thickness or both have been analyzed mathematically, and the findings are described in this paper. A tapered-thickness form is found to be the best practical one from the standpoint of economy of material. Conveniently usable charts are included which are applicable in the form of correction coefficients to the standard formulas for thermostatic deflection and mechanical deflection of strips of uniform thickness and width. The dual-tapered form is especially useful in reducing vibration troubles in slow-acting thermostats, and formulas are given for determining the fundamental frequency of single- or dual-tapered strips of any taper ratio.

THERMOSTATIC BIMETALS of the "low-temperature" or brass-Invar type have been used for many years in the construction of innumerable thermostatic-control devices. The substitution of stronger and more active metals for the brass component by Spencer and others during the '20's led to an impressive extension of the use of bimetals. The announcement of the manganese–Invar bimetal in 1942 gave the industry a further remarkable fundamental improvement.

Bimetals now are used almost universally in sheet form, and extensive work has been done in development of various outlines and bent shapes for which well-known simplified deflection and force formulas are available. In addition, a limited amount of progress has been made toward the useful development of bimetal rods, cones, and tapered-thickness sheets. The last-mentioned form gives promise of a substantially increased effectiveness in utilization of the material, and this, coupled with discoveries of inexpensive fabrication methods, has led to the present exploration of its characteristics. The results of these studies have been interpreted into suitable form for convenient engineering use.

Although it is well-known that unloaded bimetal strips deflect into circular curvatures in response to temperature changes, the temperature-deflection formulas and constants in common use are based upon the assumption of parabolic curvatures. Such an approximation is reasonably acceptable, as the errors are very small for the short arcs involved and the parabolic formulas are vastly simpler than the circular ones. The assumption of parabolic curvatures will be retained throughout the present studies.

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Deflection Characteristics

The deflection characteristic of an initially flat bimetal strip of uniform thickness, supported at one end and subject to uniform temperature variations, is given approximately by the parabolic expression:

$$\delta = \frac{K\Delta l^2}{t_0} \tag{1}$$

where

K = deflection constant governed by composition of strip
l = distance along strip from support
t_0 = thickness of strip
Δ = temperature change of strip
δ = deflection of strip at distance l from support, due to temperature change Δ

If we differentiate equation 1, the slope of the strip at any point is

$$\frac{d\delta}{dl} = \frac{2K\Delta l}{t_0} \tag{2}$$

and if we differentiate again the rate of change of slope is

$$\frac{d^2\delta}{dl^2} = \frac{2K\Delta}{t_0} \tag{3}$$

If we consider now a bimetal strip of variable thickness t, the rate of change of slope will be

$$\frac{d^2\delta}{dl^2} = \frac{2K\Delta}{t} \tag{4}$$

If the strip tapers uniformly, it will appear as shown in Figure 1, where

L = length of strip
t_0 = thickness of strip at base or support
t_1 = thickness of strip at free end
t = thickness of strip at any point
l = distance along strip from t_0 to t_1
b = width

$$R_t = \text{taper ratio} = \frac{t_1}{t_0}$$

It will be seen from Figure 1 that

$$\frac{t_0 - t_1}{L} = \frac{t - t_1}{L - l}$$

and

$$t = t_0\left[1 - \left(\frac{1 - R_t}{L}\right)l\right] \tag{5}$$

If we substitute equation 5 in equation 4, the rate of change of slope of the tapered strip of Figure 1 is

$$\frac{d^2\delta}{dl^2} = \frac{2K\Delta}{t_0\left[1 - \left(\frac{1 - R_t}{L}\right)l\right]} \tag{6}$$

If we integrate twice, the deflection characteristic of a uniformly tapering bimetal strip is found to be

$$\delta = \frac{K\Delta l^2}{t_0} \cdot \frac{2L}{l(1 - R_t)} \times \left\{\left[1 - \frac{L}{l(1 - R_t)}\right] \ln \frac{1}{1 - \frac{(1 - R_t)l}{L}} + 1\right\} \tag{7}$$

The deflection of the free end ($l = L$) is

$$\delta = \frac{K\Delta L^2}{t_0} \cdot \frac{2}{(1 - R_t)}\left\{1 - \frac{R_t}{1 - R_t} \ln \frac{1}{R_t}\right\} \tag{8}$$

With reference to equation 1, the ratio of deflection of a tapered-thickness strip to that of a uniform strip of identical thickness at the support is expressible in terms of the taper ratio alone, as follows:

$$\frac{\delta \text{ tapered strip}}{\delta \text{ uniform strip}} = \frac{2}{(1 - R_t)}\left\{1 - \frac{R_t}{1 - R_t} \ln \frac{1}{R_t}\right\} \tag{9}$$

and this expression may be treated as a correction to be applied to the conven-

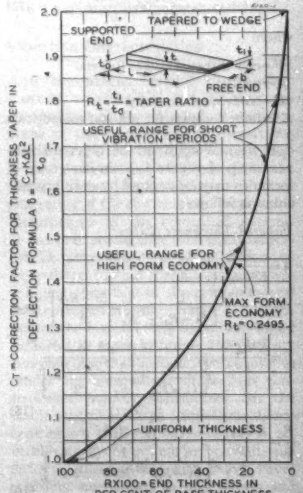

Figure 1. Deflection characteristics of flat bimetal strips having uniformly tapered thickness

Supported rigidly at thick end

tional formula for bimetal deflections when the deflection of any tapered-thickness bimetal strip is to be found. This correction will be designated C_T and may be conveniently represented graphically, as in Figure 1. The conventional formula for the deflection of a bimetal strip may now be generalized as follows:

$$\delta = \frac{C_T K L^2}{t_t} \tag{10}$$

where C_T is a form factor for the strip and is obtainable directly from Figure 1. From this figure it is found that the deflection of any flat bimetal strip is exactly doubled if the strip is uniformly tapered to zero thickness at the free end. The width evidently does not enter into this relation.

Force Characteristics

Consider the general case of a flat bimetal strip rigidly supported at one end, of a negligible weight, and loaded as a cantilever beam, at the free end by a concentrated load. If the strip is nontapered as well as flat and of uniform width, the following conventional formulas are readily available from handbooks.

Uniform-Thickness Strips:

$$\text{Deflection} = \delta = \frac{4FL^3}{Eb_0t_0^3} = \frac{FL^3}{K^1b_0t_0^3} \tag{11}$$

$$\text{Force} = F = \frac{Eb_0t_0^3\delta}{4L^3} = \frac{K^1b_0t_0^3\delta}{L^3} \tag{12}$$

$$\text{Stiffness} = \frac{F}{\delta} = \frac{Eb_0t_0^3}{4L^3} = \frac{K^1b_0t_0^3}{L^3} \tag{13}$$

where

F = concentrated load at free end
b_0 = width
E = modulus of elasticity
K^1 = force constant for bimetal composition

If we now consider the tapered-thickness strip of Figure 1, a similar group of formulas may be derived by ordinary calculus as follows:

Tapered-Thickness Strips:

$$\delta = \frac{FL^3}{K^1b_0t_0^3} \cdot \frac{3}{(1-R_t)^2} \times \left[\frac{1}{(1-R_t)} \ln \frac{1}{R_t} - \frac{(3-R_t)}{2}\right] \tag{14}$$

$$F = \frac{K^1b_0t_0^3\delta}{L^3} \cdot \frac{(1-R_t)^2}{3\left[\frac{1}{(1-R_t)} \ln \frac{1}{R_t} - \frac{(3-R_t)}{2}\right]} \tag{15}$$

$$\frac{F}{\delta} = \frac{K^1b_0t_0^3}{L^3} \cdot \frac{(1-R_t)^2}{3\left[\frac{1}{(1-R_t)} \ln \frac{1}{R_t} - \frac{(3-R_t)}{2}\right]} \tag{16}$$

Here again the effect of tapering the thickness of the strip can be expressed as a correction C_{Tt} expressed in terms of R_t, which may be applied to equations 14, 15, and 16, resulting in generalized equations as follows:

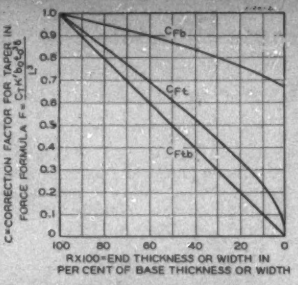

Figure 2. Force characteristics of flat bimetal strips having uniformly tapered dimensions and supported rigidly at thick end: cantilever load on free end

C_{Tt}—Thickness taper
C_{Tb}—Width taper
C_{Ttb}—Equal thickness and width taper combined

$$F = \frac{FL^3}{C_{Tt}K^1b_0t_0^3} \tag{17}$$

$$F = \frac{C_{Tt}K^1b_0t_0^3\delta}{L^3} \tag{18}$$

$$\frac{F}{\delta} = \frac{C_{Tt}K^1b_0t_0^3}{L^3} \tag{19}$$

where

$$C_{Tt} = \frac{(1-R_t)^2}{3\left[\frac{1}{(1-R_t)} \ln \frac{1}{R_t} - \frac{(3-R_t)}{2}\right]} \tag{20}$$

Specific values of C_{Tt} for any taper ratio may be obtained conveniently from a plot of this expression as given in Figure 2. The conventional bimetal force formulas therefore may be used for tapered bimetals provided the appropriate correction factors from Figure 2 are applied to the values.

For comparative purposes, similar expressions and curves have been derived for the cases of width-tapered bimetal strips of uniform thickness, and bimetal strips tapering in both width and thickness.

C_{Tb}(width tapered only)

$$= \frac{(1-R_b)^2}{3\left[\frac{R_b^2}{(1-R_b)} \ln \frac{1}{R_b} - \frac{3R_b-1}{2}\right]} \tag{21}$$

$$C_{Ttb}(\text{equal dual taper}) = R_t = R_b \tag{22}$$

where

R_b = width-taper ratio $= \frac{b_1}{b_0}$

b_1 = width of strip at free end

Economy

In judging the relative merits of different tapered forms of thermostatic bimetal members, it will be useful to determine the amount of work performed per unit weight of each taper form under comparable conditions. From such values a criterion will be established and called the "form-economy" characteristic of the shape. This criterion will be defined as the ratio of the work obtainable from a bimetal piece of a specified form to the work obtainable from a piece of flat bimetal of uniform cross section and of equal total weight.

Form economy will be indicated by the symbol ϵ, and for the flat reference standard under this definition ϵ is taken as unity and may be expressed more formally as follows:

$\epsilon = 1.00 =$ constant × work required to restore free end of flat strip of uniform section to original position after deflection due to unit temperature change ÷ weight of bimetal strip
$=$ (constant × ½ × unloaded thermostatic deflection × force to restore bimetal end by amount of thermostatic deflection) ÷ (volume of bimetal × density of bimetal)

$$= \frac{k_f \times \frac{1}{2} \times \frac{K\Delta L^2}{t_t} \times \frac{K^1b_0t_0^3\delta}{L^3}}{b_0t_0L \times W} \tag{23}$$

Since by equation 1,

$$\delta = \frac{K\Delta L^2}{t_t}$$

$$\epsilon = 1.00 = \frac{k_f \times \frac{1}{2} \times \left(\frac{K\Delta L^2}{t_t}\right)^2 \times \frac{K^1b_0t_0^3}{L^3}}{b_0t_0L \times W} \tag{24}$$

$$= \frac{k_fK^2K^1\Delta^2}{2w} \tag{24a}$$

and

$$k_f = \frac{2w}{K^2K^1\Delta^2} \tag{25}$$

For a tapered bimetal, the form economy will be

$$\epsilon = \frac{2w}{K^2K^1\Delta^2} \times \frac{1}{2} \times \left(\frac{C_TK\Delta L^2}{t_t}\right)^2 \times \frac{C_T^2K^1b_0t_0^3}{L^3} \Big/ \text{volume} \times W \tag{26}$$

or

$$\epsilon = \frac{C_T^3C_TLb_0t_0}{\text{volume}} \tag{26a}$$

But volume can be expressed in terms of b_0, t_0, and L, and the taper ratio R, for example:

Volume (tapered thickness, parallel edges)

$$= b_0t_0L\left(\frac{1+R_t}{2}\right) \tag{27}$$

Volume (uniform thickness, tapered edges),

$$= b_0t_0L\left(\frac{1+R_b}{2}\right) \tag{28}$$

Volume (tapered thickness, tapered edges $[R_b = R_t = R_{tb}]$)

$$= b_0t_0L\left(\frac{1+R_{tb}+R_{tb}^2}{3}\right) \tag{29}$$

Consequently, from equation 26a,

ϵ_t(tapered thickness, parallel edges)

$$= \frac{2C_T{}^3C_{T1}}{(1+R_t)} \quad (30)$$

ϵ_b(uniform thickness, tapered edges)

$$= \frac{2C_{T3}}{(1+R_b)} \quad (31)$$

ϵ_{tb}(tapered thickness, tapered edges [$R_b = R_t$])

$$= \frac{3C_T{}^3}{1+R_M+\frac{1}{R_M}} \quad (32)$$

The form economy of the foregoing shapes has been evaluated for various values of taper ratio and the results plotted in Figure 3. Maximum values of form economy and corresponding taper ratios were determined by calculus. These maxima occur as given in Table I. From an inspection of these values, it is evident that for flat bimetal strips of the taper forms studied, the most economical in point of work performed per unit weight is the conventional bimetal sheet of uniform thickness, and having the side edges tapering to a point at the free end. Unfortunately, however, this form seldom can be utilized in any practical thermostatic construction, as it is always necessary to make the free end of the bimetal strip physically wide enough to carry an electric contact or to actuate a co-operating working member. For any value of width–taper ratio of more than 0.1, which generally is below a usable minimum, the form economy is seen to have fallen off to approximately less than that for the thickness-tapered bimetal, and the latter form would take preference.

Maximum form economies for the thickness-tapered bimetals appear in the taper-ratio region between $R = 0.2$ to 0.3. In this region the metal will perform approximately one-third more work than it would if shaped as a conventional uniformly thick strip. If the bimetal can be produced at costs appreciably less than 130 per cent of the cost of flat bimetal stock, then the tapered-thickness bimetal construction becomes the most economical form for general flat-strip applications. Actual costs of the tapering process are said to be negligible compared to the gain in performance.

Fortunately, a thickness-tapered bimetal strip of maximum form economy will have a free-end thickness lying between one fourth to one fifth of the base thickness, which usually will be quite adequate mechanically for mounting of electric contacts. This form, therefore, can be recognized as a new and very useful embodiment of the bimetallic thermostatic strip.

Table I. Maximum Form Economy and Taper Ratio for Several Taper Forms

Form	ϵ_{Max}	Taper Ratio for ϵ_{Max}
Tapered thickness / Uniform width	1.304	0.2495
Uniform thickness / Tapered width	1.333	0.000
Tapered thickness / Tapered width ($R_t = R_b$)	1.296	0.435

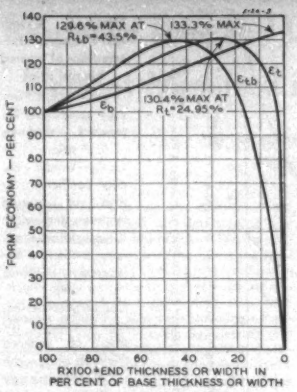

Figure 3. Form economy of flat bimetal strips of various taper forms

ϵ_t—Thickness taper
ϵ_b—Width taper
ϵ_{tb}—Equal thickness and width taper combined

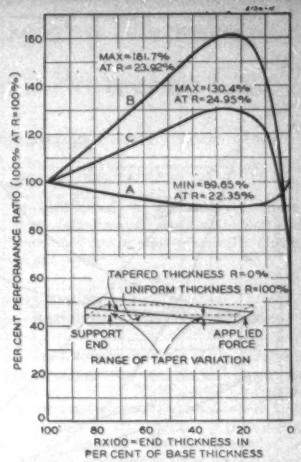

Figure 4. Variation in bimetal-strip characteristics with change in thickness taper

Volume, width, and length held constant

A—Deflection
B—Stiffness
C—Form economy

It will be noticed that the dual-tapered form yields a form economy nearly equal to that for the tapered-thickness strip if a taper ratio of somewhat less than 0.5 is used for the former. This form is rendered uneconomical, however, by the practical consideration that cutting of width-tapered strips from thickness-tapered stock would produce an appreciable quantity of scrap, rendering the high economy unrealizable.

In order to visualize better the manner in which the tapered-thickness form improves the form economy of the bimetal, Figure 4 has been prepared. In this figure, a flat bimetal strip has been subjected to a progressive alteration of form consisting in a shift of the angle between faces over the range from parallelism to wedge form. The total quantity of metal, as well as all other factors, has been held constant during this metamorphosis in order to show precisely how the properties of the strip are modified by the change. Figure 4 reveals that the deflection decreases during the transformation until a taper ratio of 22.35 per cent is reached, at which point the deflection is 89.65 per cent that of the original flat strip. Beyond this point the deflection again increases until the full original value is regained at the point where the strip reaches wedge form. The base thickness evidently is doubled at this time. During this transformation the stiffness of the member increased much more rapidly, however, reaching 161.7 per cent of the stiffness of the flat strip at $R = 23.92$ per cent. The net result is an increase in form economy to a maximum of 130.4 per cent at $R = 24.95$ per cent, which confirms this finding from Figure 3.

Vibration Characteristics

In slow-acting bimetal thermostatic controls considerable trouble may be encountered at the moment of make or break of the electric control circuit, especially if the rate of temperature change is very slow, because of vibrations of the bimetal strip. Such vibrations produce chattering of the contacts and consequent disturbances in the controlled system. It has been found that such disturbances can be prevented if the bimetal member be so designed that its natural frequency is higher than that of the components of the controlled system. Single or dual tapers of the bimetal strip have been found sufficient in some instances to eliminate completely such vibration troubles and to render the slow-acting thermostat construction entirely satisfactory for the stable control of relays. Small telephone-type relays which formerly chattered severely when controlled by conventional flat-strip thermostats with heavy silver contacts, were found to close slowly and remain closed when the bimetal strip was tapered in width and thickness and the contact reduced in weight. Elimination of thickness taper only restored the chattering condition.

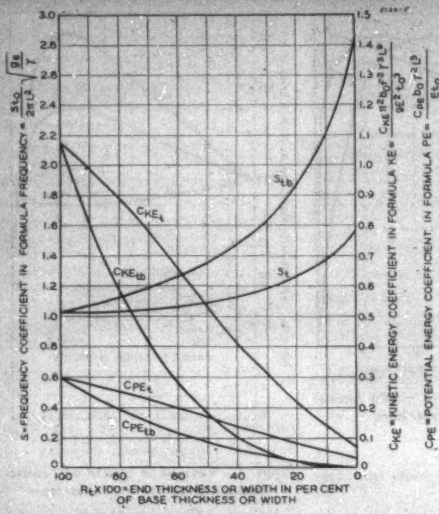
S = FREQUENCY COEFFICIENT IN FORMULA FREQUENCY = $\frac{Sk_0}{2\pi L^2}\sqrt{\frac{gE}{\gamma}}$
C_{KE} = KINETIC ENERGY COEFFICIENT IN FORMULA KE = $C_{KE}\frac{b_0 b_0^3 f^2 \gamma^2 L^5}{gE^2 t_0^3}$
C_{PE} = POTENTIAL ENERGY COEFFICIENT IN FORMULA PE = $C_{PE}\frac{b_0 b_0^3 L^3}{Et_0}$
S_{tb}
C_{KE_t}
$C_{KE_{tb}}$
S_t
C_{PE_t}
$C_{PE_{tb}}$
R_t X 100 = END THICKNESS OR WIDTH IN PER CENT OF BASE THICKNESS OR WIDTH

Figure 5. Energy and frequency characteristics of tapered bimetal strips

C_{KE_t} = kinetic-energy coefficient for tapered-thickness strip

$C_{KE_{tb}}$ = kinetic-energy coefficient for strip of tapered thickness and width

C_{PE_t} = potential-energy coefficient for tapered-thickness strip

$C_{PE_{tb}}$ = potential-energy coefficient for strip of tapered thickness and width

S_t = frequency coefficient for tapered thickness strip

S_{tb} = frequency coefficient for strip of tapered thickness and width

An analysis of the natural frequencies of tapered bimetal strips has been made, to determine the vibration characteristics as a function of form. The frequencies (fundamental only) were calculated for plain flat strips of various tapers, with rigid support at the base assumed and zero mass carried by the free vibrating end. If the contact actually carried by the end of such a tapered strip in practice is light in weight compared to the weight of the strip, the contact weight will have slight effect on the frequency of the strip, and the results of the present analysis will be applicable. If the contact is made large and heavy, its weight will predominate in the determination of frequency, and tapering of the supporting strip will be defeated.

The frequencies were here determined by the method of Rayleigh in which the potential and kinetic energies of the vibrating strip are equated. The results are believed accurate to within 0.5 to 1.5 per cent. An exact mathematical determination would be difficult and very laborious and will not be attempted as the accuracy of the present method is entirely adequate.

The steps in computation of the natural frequencies are given in Table II for three flat-strip forms; the conventional strip of uniform thickness, the thickness-tapered wedge and the pyramidal or dual taper.

Expressions similar to those given in Table II also were derived for the more general case of bimetal strips of taper R_t or R_{tb}. These expressions yield the values given in Table II, columns 1 and 2, when values of $R_t = 100$ per cent and $R_t = 0$ per cent, respectively, are substituted. The complete expressions are given in Appendix I. The coefficients for the expressions for natural frequency for all ratios are plotted in Figure 5.

The curves of frequency-versus-taper ratio show the wedge form to vibrate about 50 per cent faster than a strip of uniform thickness. For a usable and economical strip of taper ratio 0.25, the increase in frequency over that of a flat strip is only about 20 per cent. Consequently, where high frequency of the strip is the predominant design consideration, thickness tapering alone is only slightly effective.

Figure 5 similarly shows the dual wedge or pyramid to have a theoretical maximum increase in frequency to over $2^1/_2$ times the value for strips of uniform thickness and width. For practically usable strips, increases to 200 to 220 per-cent frequency probably cannot be exceeded. In those cases, however, in which suppression of vibration troubles is of much greater importance than economy of material, the dual taper is of considerable practical value.

It is interesting to note that thermostatic deflection and period of vibration are governed by the same dimensional parameters, L^2/t_0. Because of this fact, short vibration periods cannot be obtained by modifying the physical proportions of any type of strip when a specified thermostatic deflection is required. Change of shape appears to be the most convenient means of obtaining independent frequency adjustment of the thermostatic strip.

Appendix I

Frequency of Tapered-Thickness Strips

$$\text{Thickness } t = t_0\left[(1-R_t)\frac{(L-l)}{L}+R_t\right] \quad (33)$$

$$\text{Bending moment} = \frac{\gamma b_0 t_0}{2}(L-1)^2\times\left[\frac{(1-R_t)(L-1)}{3L}+R_t\right] \quad (34)$$

Table II. Natural Frequencies of Flat Bimetal Strips

Fundamentals Only

Form	Uniform Thickness	Wedge	Pyramid
Moment of inertia	$\frac{b_0 t_0^3}{12}$	$\frac{b_0 t_0^3 (L-l)^3}{12L^3}$	$\frac{b_0 t_0^3 (L-l)^4}{12L^4}$
Bending moment	$\frac{\gamma b_0 t_0 (L-l)^2}{2}$	$\frac{\gamma b_0 t_0 (L-l)^3}{6L}$	$\frac{\gamma b_0 t_0 (L-l)^4}{12L^2}$
Deflection of strip under its own weight	$\frac{6\gamma}{Et_0^2}\left(\frac{L^2 l^2}{2}-\frac{Ll^3}{3}+\frac{l^4}{12}\right)$	$\frac{\gamma L^2 l^2}{Et_0^2}$	$\frac{\gamma L^2 l^2}{2Et_0^2}$
Maximum velocity at any point if free end is released from rest under its own weight	$\frac{12\pi f\gamma}{Et_0^2}\left(\frac{L^2 l^2}{2}-\frac{Ll^3}{3}+\frac{l^4}{12}\right)$	$\frac{2\pi f\gamma L^2 l^2}{Et_0^2}$	$\frac{\pi f\gamma L^2 l^2}{Et_0^2}$
Kinetic energy under maximum velocity	$\frac{1.1556\pi^2 b_0 f^2 \gamma^2 L^5}{gE^2 t_0^3}$	$\frac{0.0666\pi^2 b_0 f^2 \gamma^2 L^5}{gE^2 t_0^3}$	$\frac{0.00476\pi^2 b_0 f^2 \gamma^2 L^5}{gE^2 t_0^3}$
Potential-energy change	$\frac{0.3 b_0 \gamma^2 L^5}{Et_0}$	$\frac{0.04166 b_0 \gamma^2 L^5}{Et_0}$	$\frac{0.00833 b_0 \gamma^2 L^5}{Et_0}$
Frequency from $KE = PE$	$\frac{1.02 t_0}{2\pi L^2}\sqrt{\frac{gE}{\gamma}}$	$\frac{1.58 t_0}{2\pi L^2}\sqrt{\frac{gE}{\gamma}}$	$\frac{2.646 t_0}{2\pi L^2}\sqrt{\frac{gE}{\gamma}}$

where

γ = density of material

f = natural frequency of strip

g = acceleration of gravity

Moment of inertia

$$= \frac{b_b s_b}{12}\left[(1-R_t)\frac{(L-1)}{L}+R_t\right]^3 \quad (35)$$

Deflection of strip under its own weight

$$= \frac{2\gamma L^4}{Et_b^3}\left[\frac{l^3}{2(1-R_t)^3}+\frac{LR_t^3(3-R_t)l}{(1-R_t)^3}+\frac{3L^2R_t^2}{(1-R_t)^4}\ln\frac{L-(1-R_t)l}{L}+\frac{L^2R_tl}{(1-R_t)^2[L-(1-R_t)l]}\right] \quad (36)$$

Kinetic energy

$$= \frac{\pi^2 b_b f^2\gamma^2 L^9}{gE^2t_b^3(1-R_t)^9}\left[(16R^8-96R^7+98R^6-16R^5+12R^4)\ln\frac{1}{R_t}-36R_t^6\left(\ln\frac{1}{R_t}\right)^2-2R_t^{10}+22.66R_t^9-86.266R_t^8+124.8R_t^7-67.5R_t^6+18.933R_t^5-13R_t^4+4.266R_t^3-1.966R_t^2+0.0666\right] \quad (37)$$

Potential-energy change

$$= \frac{b_b\gamma^2L^5}{Et_b(1-R_t)^5}\left[\frac{3}{2}R_t^4\ln\frac{1}{R_t}-\frac{R_t^5}{3}+2R_t^3-\frac{15}{8}R_t^2+\frac{2}{3}R_t-\frac{R_t^2}{2}+\frac{1}{24}\right] \quad (38)$$

Frequency was found for values of R_t by equating kinetic and potential energies.

Frequency of Dual-Tapered Strips

$$\text{Thickness} = t_b\left[(1-R_{bt})\frac{(L-l)}{L}+R_{bt}\right] \quad (39)$$

$$\text{Width} = b_b\left[(1-R_{bt})\frac{(L-l)}{L}+R_{bt}\right] \quad (40)$$

Bending moment

$$= \frac{\gamma b_b s_b L^5}{12(1-R_{bt})^3}\left\{\left[(1-R_{bt})\frac{(L-l)}{L}+R_{bt}\right]^4-R_{bt}^3\left[\frac{4(1-R_{bt})(L-l)}{L}+R_{bt}\right]\right\} \quad (41)$$

Moment of inertia

$$= \frac{b_b s_b}{12}\left[(1-R_{bt})\frac{(L-l)}{L}+R_{bt}\right]^3 \quad (42)$$

Deflection of strip under its own weight

$$= \frac{\gamma L^4}{Et_b(1-R_{bt})^4}\left[\frac{u^3}{2}-\frac{2R_{bt}u^3}{u}+\frac{R_{bt}^4}{2u^2}-(1+2R_{bt}^3-R_{bt}^4)u+\frac{1}{2}+4R_{bt}^3-\frac{3R_{bt}^4}{2}\right] \quad (43)$$

where

$$u = 1-(1-R_{bt})\frac{1}{L}$$

Kinetic energy

$$= \frac{\pi^2 b_b f^2\gamma^2 L^9}{gE^2t_b^3(1-R_{bt})^9}\left[4R_{bt}^7\ln R_{bt}-\frac{2R_{bt}^{12}}{5}+\frac{31R_{bt}^{12}}{10}-\frac{101R_{bt}^{11}}{10}+\frac{52R_{bt}^{10}}{3}-\frac{224R_{bt}^9}{15}+\frac{7R_{bt}^8}{10}+\frac{204R_{bt}^7}{35}-\frac{12R_{bt}^6}{5}+\frac{2R_{bt}^5}{5}+\frac{23R_{bt}^4}{30}-\frac{3R_{bt}^3}{10}+\frac{1}{210}\right] \quad (44)$$

Response Time and Lag of a Thermometer Element Mounted in a Protecting Case

W. N. GOODWIN, JR.
FELLOW AIEE

Synopsis: In this paper equations are derived and applied for determining the response time and temperature lag, in general, of a body which exchanges heat with a medium indirectly through a second body. Application is made to a thermometer element mounted in a protecting case, with specific reference to a resistance-type thermometer such as is used for aircraft and marine purposes. The temperature distribution along the stem and the errors resulting when the head of the bulb and medium differ in temperature also are derived.

IN THE DESIGN of many forms of thermometers it is frequently customary and often necessary to mount the active element within a protecting case. This is particularly true in the case of resistance and bimetal types and often true with the thermocouple and ordinary mercury types.

When protecting cases are used, the active element is not in direct contact with the surrounding medium, the temperature of which is to be measured, but its exchange of heat, in acquiring the temperature of the medium, must take place through the protecting case and through the thermal contact between the element and case.

Under the conditions referred to, there is an additional time lag in the indications of the thermometer element over that which would result if the element were in direct contact with the medium, when the temperature of the latter differs from it or changes with time.

The object of this analysis is to determine the equations of the cooling and heating curves of an element contained in a protecting case, from which design data and operating characteristics can be determined for specified conditions. Part of this analysis was done in 1921 and completed and applied practically during recent years.

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Application to a Resistance-Type Thermometer

To make the analysis of this problem of more practical use, we will direct our attention to a specific device by considering a resistance-type thermometer bulb developed by an associate of the author, K. M. Lederer. This is illustrated in Figure 1, cut away to show the construction. The analysis, however, is perfectly general and applies to any object exchanging heat with a surrounding medium indirectly, through another body in direct contact with the medium.

In this part of the paper the final equations and their applications are given. The complete derivations, however, are given in the appendixes.

The thermometer element *m* in Figure 1 consists of a wire resistor wound on a thin-walled tube and electrically insulated from it. This tube is contained in a protecting tube *M* and is in good thermal contact with it.

The protecting tube containing the resistor element is secured to the head *B* through which the connections to the resistor element pass to the indicating instrument.

In the derivation of the equations the following quantities appear, MS/h_1, ms/h_2, and ms/h_1; in which *M* and *m* are the masses, *S* and *s* the specific heats of the protecting tube and thermometer element, respectively, and h_1 and h_2 the rates of heat transfer per degree difference in temperature, from the protecting tube to the surrounding medium, and from the thermometer element to the protecting tube, respectively, all corresponding to the heat-exchange area. The definitions of these and other symbols are given in the list of symbols. These

Potential-energy change

$$= \frac{b_b\gamma^2L^5}{Et_b(1-R_{bt})^5}\left[-\frac{R_{bt}^8}{8}+\frac{R_{bt}^7}{2}-\frac{2R_{bt}^6}{3}+\frac{R_{bt}^5}{5}+\frac{R_{bt}^4}{4}-\frac{R_{bt}^3}{6}+\frac{1}{120}\right] \quad (45)$$

Frequency was similarly determined from the energy expressions.

In all cases the foregoing general equations are reducible to the specific cases for $R=0$ and $R=1$ as given in Table II in the body of this paper. In order to accomplish such reductions it is usually necessary to apply L'Hopital's theorem for the evaluation of indeterminate forms. In the case of the expressions for kinetic energy it was necessary to perform nine successive differentiations.

have the dimensions of time, which we will designate as t_1, t_2 and t_m, respectively, where $t_1 = MS/h_1$ is the time constant of the protecting tube relative to the surrounding medium, $t_2 = ms/h_2$ is the time constant of the resistor element relative to the protecting tube, and t_m is the mutual time constant ms/h_1 of the resistance element relative to the surrounding medium acting through the protecting case. That is, it is the time constant the inner tube would have if its heat were exchanged with the surrounding medium from the surface of the protecting tube.

Physically considered, the time constant is the time required for the body to change one degree in temperature, for the specified rate of heat exchange, if the temperature difference is maintained at one degree.

Thermometer Transferred From a Hotter to a Cooler Medium

If the thermometer bulb, having its resistor element and protecting tube both initially at the temperature θ_0 is suddenly immersed in the cooling medium at a temperature T_c, then the ratio of the temperature elevation $(\theta - T_c)$ of the element above that of the cooling medium at any time t, to the initial elevation $(\theta_0 - T_c)$, is, as shown in Appendix I,

$$\frac{\theta - T_c}{\theta_0 - T_c} = \frac{1}{P} e^{-\left[\left(\frac{t}{t_0}\right)\sqrt{P^2+1}\right]} \times \sinh_1\left[P\left(\frac{t}{t_0}\right) + \sinh^{-1} P\right] \quad (1)$$

where

$$P = \sqrt{\frac{(t_1+t_2+t_m)^2}{4t_0^2} - 1}$$

and

$$t_0 = \sqrt{t_1 t_2}$$

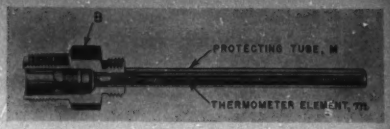
Thermometer Transferred From a Cooler to a Hotter Medium

If the initial temperature θ_0 of the thermometer element is lower than that of the surrounding medium T_c, then the resulting heating curve is exactly similar to the cooling curve previously given, except that it is reversed as shown in Figure 3 in accordance with the following equation, as shown in Appendix II,

$$\frac{\theta - \theta_0}{T_c - \theta_0} = 1 - \frac{1}{P} e^{-\left[\left(\frac{t}{t_0}\right)\sqrt{P^2+1}\right]} \times \sinh\left[P\left(\frac{t}{t_0}\right) + \sinh^{-1} P\right] \quad (2)$$

To apply these equations to a practical device, let us consider the resistance-thermometer bulb cooled in various media for which the constants given in Table I have been determined experimentally. As the inner and protecting tubes are actually in contact in this case, it is convenient to use values for M, m, h_1, and h_2 per square centimeter of contact area.

Figure 1. Resistance-type thermometer bulb, cut away to show internal construction



Cooling curves derived from this equation for the tabulated values for P and t_0 are shown in Figure 2. As an example, assume that a bulb is heated to 100 degrees centigrade and suddenly plunged into ice water at zero degrees centigrade, it will fall to ten degrees centigrade in 8.3 seconds.

The curves in Figure 2 are based upon the time t as the independent variable. If t/t_0 is made the independent variable, the curves become more general and will apply to devices of any time constant, consistent with the value of P. Such a family of curves is shown in Figure 3, which for the resistance-type thermometer, range from water to still-air cooling.

Mechanical Analogy

The temperature equations previously given have the same form as that for an aperiodic mechanical motion derived by the author in about the year 1908, namely:

$$\frac{\theta}{\phi} = \frac{1}{\sqrt{n^2-1}} e^{-2\pi n\left(\frac{t}{T_0}\right)} \times \sinh\left[2\pi\sqrt{n^2-1}\left(\frac{t}{T_0}\right) + \sinh^{-1}\sqrt{n^2-1}\right] \quad (3)$$

in which, when applied to a spring-controlled damped instrument, for example, ϕ is the initial deflection, θ the deflection after a time t given in terms of a time constant T_0 which is the undamped period, and n the ratio of the actual to the critical damping coefficient, designated by the author as the specific damping coefficient.

When the constants in equations 1 and 2 are equated to those given in equation 3, it will be found that n corresponds to $\sqrt{P^2+1}$, and T_0 to $2\pi t_0$.

If, therefore, a permanent-magnet movable-coil-type instrument has an undamped period of $T_0 = 2\pi t_0$ seconds and is damped to an amount such that $n = \sqrt{P^2+1}$, then the motion of the pointer toward zero, as a function of time, will follow the same curve as the thermal system having the constants t_0 and P.

Temperature Lag

When a thermometer is used to measure the temperature of a medium, which is changing in temperature, the indication of the thermometer lags behind the temperature of the medium as a result of the heat capacity of the thermometer and the thermal resistance to the exchange of heat between the medium and the thermometer element. An example of this condition occurs when measurements are made of the surrounding air from an airplane which is changing its altitude. Assume that a thermometer has initially the same temperature as the surrounding medium. Then let the temperature of the medium change at a constant rate of r degrees per second. The indication of the thermometer will start to follow, relatively slowly at first, but, as the difference in temperature or lag increases, the change in indication of the thermometer increases its rate until finally it approaches the same rate r as that of the change in temperature of the medium. This final difference in temperature then is maintained and is the maximum value of the lag.

The value of the lag in indication for a thermometer element in a protecting case, for an increasing temperature, relative to the final lag, at any time t after the initial change, as shown in Appendix III, is

$$\frac{T_a - \theta}{L} = 1 - \frac{1}{2P\sqrt{P^2+1}} e^{-\left[\left(\frac{t}{t_0}\right)\sqrt{P^2+1}\right]} \times \sinh\left[P\left(\frac{t}{t_0}\right) + \sinh^{-1} 2P\sqrt{P^2+1}\right] \quad (4)$$

where L is the final and maximum value of the lag, and is

$$L = 2rt_0\sqrt{P^2+1} = r(t_1+t_2+t_m) \text{ degrees} \quad (5)$$

and r is the rate of change in temperature in degrees per second, which is positive for increasing and negative for decreasing temperatures.

This shows that the lag is a simple function of the three time constants of the thermometer bulb or other device.

For a falling temperature, the lag equation is the same as equation 4 except that r becomes negative and therefore L is negative, and the left-hand member becomes $(\theta - T_a)/L$, whereas the right-hand member is unchanged.

Figure 4 gives curves showing the increase of lag with time, for various values of time constants as represented by P, in terms of time as a function of the time constant t_0 of the thermometer bulb or other device.

The ranges in values of P illustrated are perfectly general, but as applied to a resistance-type thermometer they cover ambient media from water to still air.

As a specific example, let us determine the temperature lag of the resistance thermometer previously referred to, for which $P = 0.780$, and $t_0 = 3.32$ seconds when immersed in air moving at a speed of 50 miles per hour. Assume, for example, that the air is changing in tem-

perature at a rate of five degrees centigrade per minute = (1/12) degree per second; then the maximum lag is, from equation 5,

$$L = 2 \times (1/12) \times 3.32 \times \sqrt{(0.780)^2 + 1} = 0.702 \text{ degree centigrade}$$

The time for the lag to attain any fractional part of its final value can be determined from the curves in Figure 4 derived from equation 4. By interpolating between curves for $P = 0.5$ and $P = 1$, for $P = 0.780$, we find that the time for the lag to reach, for example 90 per cent of its maximum value, is approximately $5.2 \times t_0 = 5.2 \times 3.32 = 17.3$ seconds.

The same curves may be used for both increasing and decreasing temperatures.

Errors Resulting If Head of Bulb and Stem Differ in Temperature, Under Static Conditions

Let us assume that the bulb is screwed into the walls of a tank containing a material the temperature of which is to be measured and that the tank and therefore the head of the bulb have a temperature differing from that of the material. We shall determine the temperature at any point along the stem and also determine the error by computing the average deviation of the stem temperature from that of the material contained in the tank.

In Figure 5 the sketch in solid lines shows the bulb screwed into the walls of a tank. Assume that the head of the bulb is at a temperature T_h, and that of the material in the tank T_c. The dotted-line portion is referred to later.

In a previous paper[1] by the author, equations are given for the temperature distribution along a conductor connected at its ends to terminals, as a function of the terminal temperatures, the ambient temperature, and the heat generated in the conductor.

If the two terminals have the same temperature, then the conductor and its terminals are symmetrical with respect to the center of the conductor. The stem of the thermometer bulb, therefore, can be considered as one half of a symmetrical conductor with terminals, the other half being shown in dotted lines in Figure 5. From symmetry it is obvious that the two halves may be considered as entirely independent, as no heat passes the mid-point of the conductor, and exactly similar but opposite heat flows and temperature distribution occur in the two sides.

Therefore, the same equations apply to the half conductor that would apply if the conductor were completed by its image shown dotted.

After modifying the general equation given in the paper referred to, to meet the conditions of the present problem, assuming that no heat is generated in the bulb itself, we have, from the reference paper:

$$\frac{\theta_x - T_c}{T_h - T_c} = \frac{\sinh (2l - x)\sqrt{\frac{cp}{ak}} + \sinh x\sqrt{\frac{cp}{ak}}}{\sinh 2l\sqrt{\frac{cp}{ak}}} \qquad (6)$$

where

T_h, T_c, and θ_x = temperatures of the head, of the surrounding medium, and of the stem at any point x, respectively

cp = heat loss per second per unit length of stem per one degree difference in temperature between stem and medium

a = cross-sectional area of tube

k = thermal conductivity of tube material

l = the length of the stem

Table I. Thermal Constants of a Resistance-Type Thermometer

Object	Quantity*	Medium: Water	Medium: Still Air	Medium: Air at 50 Miles Per Hour
Protecting Case, $M = 0.295$, $S = 0.529$	h_1	0.109	0.00151	0.0306
	h_1	1.432	100.0	5.10
Thermometer Element, $M = 0.0384$, $s = 0.916$	h_2	0.0164	0.0164	0.0164
	t_2	2.16	2.16	2.16
	t_m	0.326	22.5	1.16
Derived Constants	P	0.491	4.12	0.780
	t_0	1.76	14.7	3.32

*h_1, h_2, watts per square centimeter per degree centigrade; t_1, t_2, t_0, t_m, seconds; M, m, grams per square centimeter; S, s, joules per gram per degree centigrade; P, numeric.

Expanding the numerator, simplifying, and for ease in handling the equation express x in terms of l, letting $x = yl$, and we have

$$\frac{\theta_y - T_c}{T_h - T_c} = \frac{\cosh\left[(1-y)l\sqrt{\frac{cp}{ak}}\right]}{\cosh l\sqrt{\frac{cp}{ak}}} \qquad (7)$$

This gives the temperature at any point along the stem above that of the surrounding medium relative to the corresponding elevation in temperature of the head of the bulb above the temperature of the medium.

At the end of the tube, where $y = 1$, this reduces to

$$\frac{\theta_y - T_c}{T_h - T_c} = \frac{1}{\cosh\left[l\sqrt{\frac{cp}{ak}}\right]} \qquad (8)$$

In a resistance-thermometer bulb, for example, the constants, experimentally determined are as follows:

The convection rate in watts per centimeter length of tube per one degree centigrade, for still air, $cp = 0.0032$; for air moving at 50 miles per hour $cp = 0.0612$; and for water $cp = 0.218$.

Then, $l\sqrt{cp/ak}$ for still air is 5.45; for air moving at 50 miles per hour, 16.75; and for water, 44.7; in which $a = 0.0706$ square centimeter; $k = 0.2$ watt per centimeter cube per degree centigrade, $l = 11.4$ centimeters, and diameter of tube = 0.635 centimeter.

If we substitute these constants in equation 7, and give y various values from 0 to 1, temperature-distribution curves for the resistance-type thermometer are obtained which are shown in Figure 6.

For the more general problem of any thermometer having a stem of uniform cross section, a family of curves is shown in Figure 7, giving the distribution of temperature along the stem, for various values of $l\sqrt{cp/ak}$, when the head of the thermometer and the medium differ in temperature. Values should be considered posi-

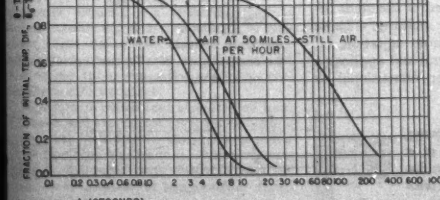


Figure 2. Cooling curves for resistance-type thermometer bulb cooled in water, still air, and in air moving at 50 miles per hour

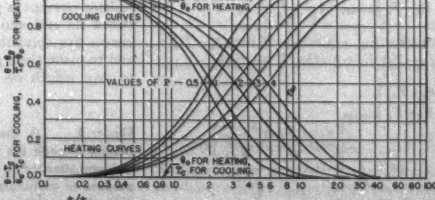


Figure 3. General cooling curves for a thermometer element in a protecting case in terms of its time constants

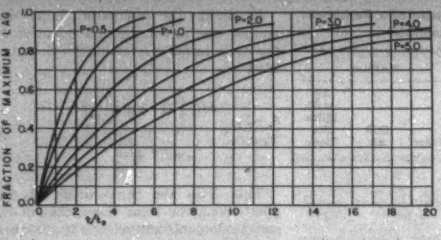


Figure 4. Temperature lag at any time, as a fraction of its maximum lag, of a thermometer in a protecting case, immersed in a medium changing in temperature at a constant rate, in terms of its time constants

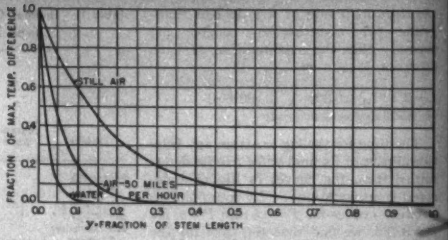


Figure 6. Distribution of temperature along a resistance-type-thermometer stem extending into a medium, as, for example, a thermometer inserted into a tank, when the head of the thermometer and the medium differ in temperature

Values are given as fractions of this difference in temperature

tive when the thermometer temperatures are higher than that of the medium, and negative when they are lower than that of the medium.

Errors

When the temperature of the head of the thermometer bulb differs from that of the medium being measured, then an error results. If a linear relationship between temperature and electrical resistance of the thermometer element throughout its length in the protecting tube is assumed, then the resistance change at any part of the tube is proportional to the change in temperature at that part of the tube. The total effect or error then, in terms of the difference in temperature $(T_h - T_c)$ between the head and the medium, is the ratio of the average deviation in temperature throughout the active part of the stem from that of the medium, to the maximum temperature difference $(T_h - T_c)$. Equation 7 gives the temperature at any point y, relative to the maximum temperature difference $(T_h - T_c)$. Assume that the resistance element extends from the end of the stem to a point y. The average temperature then can be computed by dividing the area under the curve of temperature distribution for the active part of the stem by the length of this part of the stem as a function of y, that is by $(1-y)$. The average value is then

$$\left[\frac{\theta_y - T_c}{T_h - T_c}\right]_{\text{average}} = \frac{1}{1-y}\int_y^1 \left(\frac{\theta_y - T_c}{T_h - T_c}\right) dy \quad (9)$$

Substituting equation 7 for $(\theta_y - T_c) \div (T_h - T_c)$ in equation 9 we have

$$\left[\frac{\theta_y - T_c}{T_h - T_c}\right]_{\text{average}} = \frac{1}{1-y}\int_y^1 \frac{\left[\cosh (1-y) l\sqrt{\frac{cp}{ak}}\right] dy}{\cosh l\sqrt{\frac{cp}{ak}}} \quad (10)$$

Integrating this between the limits 1 and y and simplifying, we have

$$\left[\frac{\theta_y - T_c}{T_h - T_c}\right]_{\text{average}} = \frac{\sinh \left[(1-y) l\sqrt{\frac{cp}{ak}}\right]}{(1-y) l\sqrt{\frac{cp}{ak}} \cosh l\sqrt{\frac{cp}{ak}}} \quad (11)$$

For example we shall use this equation to determine the errors in the resistance-thermometer bulb in which the resistance element extends from $y=0.17$ to $y=1$, and for which constants are already given.

For still air, by substituting $l\sqrt{cp/ak} = 5.45$ in equation 11, we have

$$\left[\frac{\theta_y - T_c}{T_h - T_c}\right]_{\text{average}} = \frac{\sinh [(1-0.17)\times 5.45]}{(1-0.17\times 5.45)\times \cosh 5.45} = 0.0878$$

Then the error in degrees is $0.0878 \times (T_h - T_c)$.

For air moving at 50 miles per hour, for which $l\sqrt{cp/ak} = 16.75$ we find

$$\left[\frac{\theta_y - T_c}{T_h - T_c}\right]_{\text{average}} = \frac{\sinh [(1-0.17)\times 16.75]}{(1-0.17)\times 16.75\times \cosh 16.75} = 0.00418$$

Then the error in degrees is $0.00418 \times (T_h - T_c)$.

For water immersion the error is negligible as is evident by inspection of Figure 6.

Figure 8 shows a family of curves giving errors as a fraction of the difference in temperature $(T_h - T_c)$ between the head of the bulb and the medium, for any length of resistor element relative to the length of the stem, assuming that the resistor element is placed in the stem between its end and the point y. These curves are computed from equation 11, and to make them general and applicable to any length or other dimensional or thermal constants they are given as a function of $l\sqrt{cp/ak}$.

List of Symbols

M = mass of the part of the protecting case which transfers heat from the thermometer element to the outside medium, grams

m = mass of thermometer element, grams

S = specific heat of material of protecting tube, watt-seconds per gram per degree centigrade

s = specific heat of material of thermometer element, watt-seconds per gram per degree centigrade

h_1 = rate of heat exchange of protecting case with outside medium, watts per degree centigrade

h_2 = rate of heat exchange of thermometer element with protecting case, watts per degree centigrade

$t_1 = MS/h_1$ = time constant of protecting case relative to outside medium, seconds

$t_2 = ms/h_2$ = time constant of thermometer element relative to protecting case, seconds

$t_m = ms/h_1$ = mutual time constant, seconds, the thermometer element would have if its exchange of heat with the external medium were effected from the surface of the protecting case

t = time, independent variable

P = for brevity $= \sqrt{\frac{(t_1+t_2+t_m)^2}{4t_0^2} - 1}$, a numeric

$t_0 = \sqrt{t_1 t_2}$ seconds

θ = temperature of the thermometer element at any time t

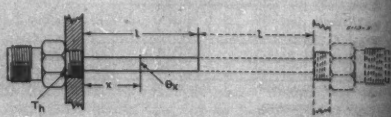


Figure 5. A thermometer passing through the wall of a tank and attached to it, for the purpose of measuring the temperature of its contents

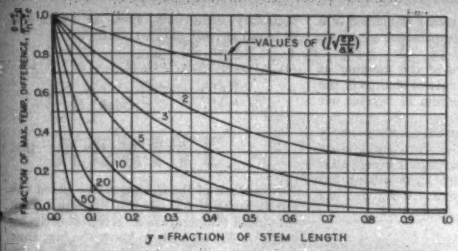


Figure 7. Temperature distribution along any thermometer stem of uniform cross section, immersed in a medium, when the temperature T_b of the thermometer head is higher than that of the medium T_a, given as a function of $l\sqrt{cp/ak}$

When T_b is lower than T_a, values are negative

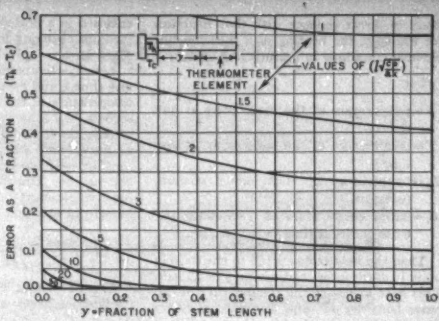


Figure 8. Errors of a resistance-type thermometer, with head at a temperature T_b and stem immersed in a medium at temperature T_a, when the resistance element extends inside the stem from its end to any position y, for various values of $l\sqrt{cp/ak}$, given as a function of y

θ_b = initial temperature of the thermometer element and protecting tube

T = temperature of the protecting case at any time t

T_a = temperature of the surrounding medium when constant

T_a = temperature of the surrounding medium at any time t, when changing

θ_x = temperature of the thermometer stem above that of medium at any distance x from head

l = length of stem of thermometer, centimeters

a = cross-sectional area of thermometer stem, square centimeters

k = thermal conductivity in watts per centimeter cube per degree centigrade

cp = heat convection from tube to surrounding medium per second per unit length of tube, watts per degree centigrade

e = base of natural logarithms

Appendix I

This analysis considers the problem of the cooling of a body indirectly by a lower constant-temperature medium through a second body in direct contact with that medium, as for example, the cooling of a thermometer element contained in a protecting case.

With reference to Figure 2, and the list of symbols, the values M and m refer in general to the masses of the outer and inner bodies, respectively, and h_1 and h_2 to the rates of heat exchanges per degree difference in temperature between the outer body and the medium, and the corresponding values between the inner and outer bodies, respectively. When the specific case of a thermometer element in a protecting case is being considered, it is convenient to consider these values per square centimeter of contact area between the element and protecting tube, since the two are practically in direct contact.

The rate at which heat is dissipated from the outer body to the cooling medium is made up of the heat loss in this body together with that lost by the inner body. In the time dt, the outer body drops dT and the inner body drops $d\theta$, in temperature. Then in the time dt

$$(T-T_a)h_1dt=-(MSdT+msd\theta) \tag{12}$$

where $MSdT$ and $msd\theta$ are the heat losses per dT and $d\theta$ for the outer and inner bodies, respectively, having masses of M and m, and specific heats of S and s, respectively.

The transmission of heat from the inner body to the outer body is equal to that lost by the inner body, and, therefore, in time dt,

$$(\theta-T)h_2dt=-msd\theta \tag{13}$$

The negative signs are used as these are decreasing functions with time.

From equation 13

$$T=\theta+\frac{ms}{h_2}\frac{d\theta}{dt}$$

Differentiating this equation for T with respect to time and substituting in equation 12 for T and dT/dt, we have after collecting terms

$$\left(\frac{MSms}{h_1h_2}\right)\frac{d^2\theta}{dt^2}+\left(\frac{MS}{h_1}+\frac{ms}{h_2}+\frac{ms}{h_1}\right)\frac{d\theta}{dt}+(\theta-T_a)=0 \tag{14}$$

Now MS/h_1, ms/h_2 and ms/h_1 have the dimensions of time, and so for brevity let them be t_1, t_2, and t_m, respectively, as the time constants of the thermometer. Substituting these time constants in equation 14 there results,

$$\frac{d^2\theta}{dt^2}+\left(\frac{t_1+t_2+t_m}{t_1t_2}\right)\frac{d\theta}{dt}+\frac{\theta-T_a}{t_1t_2}=0 \tag{15}$$

Integrating this in the usual manner by letting

$$(\theta-T_a)=e^{vt} \tag{16}$$

and substituting this in equation 15 and solving for v, we have

$$v=-\alpha\pm\sqrt{\alpha^2-\beta^2} \tag{17}$$

where for brevity

$$\alpha=\frac{1}{2}\left(\frac{t_1+t_2+t_m}{t_1t_2}\right)$$

and

$$\beta=\frac{1}{\sqrt{t_1t_2}}$$

Substituting the value for v in equation 16 we have

$$(\theta-T_a)=e^{-\alpha t}\left[ae^{t\sqrt{\alpha^2-\beta^2}}+be^{-t\sqrt{\alpha^2-\beta^2}}\right] \tag{18}$$

where a and b are constants of integration. Let $a=(1/4)(A+B)$, and $b=(1/4)(A-B)$, where A and B are constants to be determined. Then, substituting these values in equation 18, multiplying, and dividing by $\sqrt{B^2-A^2}$, expanding, and collecting terms, we have,

$$(\theta-T_a)=\left(\sqrt{B^2-A^2}\right)e^{-\alpha t}\times\sinh\left[t\sqrt{\alpha^2-\beta^2}+\sinh^{-1}\frac{A}{\sqrt{B^2-A^2}}\right] \tag{19}$$

The constants A and B are determined by applying the known boundary conditions, $\theta=\theta_b$, and $d\theta/dt=0$, at $t=0$, which, when introduced into equation 19, there results,

$$\frac{\theta-T_a}{\theta_b-T_a}=\sqrt{\frac{\beta^2}{\alpha^2-\beta^2}}e^{-\alpha t}\times\sinh\left[t\sqrt{\alpha^2-\beta^2}+\sinh^{-1}\sqrt{\frac{\alpha^2-\beta^2}{\beta^2}}\right] \tag{20}$$

Substitute in this equation the values of α and β in terms of t_1, t_2, and t_m, and for brevity let

$$P=\sqrt{\frac{\alpha^2-\beta^2}{\beta^2}}=\sqrt{\frac{(t_1+t_2+t_m)^2}{4t_0^2}-1}$$

where $t_0=\sqrt{t_1t_2}$, and we have

$$\frac{\theta-T_a}{\theta_b-T_a}=\frac{1}{P}e^{-\left[\left(\frac{t}{t_0}\right)\sqrt{P^2+1}\right]}\times\sinh\left[P\left(\frac{t}{t_0}\right)+\sinh^{-1}P\right] \tag{21}$$

which is equation 1 used in the descriptive part of this paper.

Appendix II

This analysis considers the problem of heating of a body indirectly, by a higher constant-temperature medium through a second

body in direct contact with that medium; for example, the heating of a thermometer element contained in a protecting case.

Let

θ = temperature of the inner body at any time t

T = temperature of the outer body at any time t

T_a = temperature of surrounding medium (constant)

θ_0 = initial temperature of both inner and outer bodies at time $t=0$

Then the heat transmitted to the outside body in dt from the medium is $(T_a-T)\,h_1 dt$. This heat increases the temperature of the outer body by dT, and the inner body by $d\theta$. The heat absorbed by these bodies in dt is then $MSdT+msd\theta$.

Therefore

$$(T_a-T)h_1dt = MSdT+msd\theta \tag{22}$$

The heat transmitted from the outside body to the inside body in dt is $(T-\theta)h_2dt$, and this equals the heat absorbed by the inner body, $msd\theta$.

Therefore

$$(T-\theta)h_2dt = msd\theta \tag{23}$$

It will be noted that these are the same equations as those found in the problem of the cooling bodies, namely, equations 12 and 13, and the same final equation follows:

$$\frac{d^2\theta}{dt^2}+\left(\frac{h_1+h_2+l_m}{l_0l_2}\right)\frac{d\theta}{dt}+\frac{\theta-T_a}{l_0l_2}=0 \tag{24}$$

This reduces in form, therefore, to the same equation as for the cooling problem, namely:

$$\frac{\theta-T_a}{\theta_0-T_a}=\frac{1}{P}e^{-\left[\left(\frac{t}{l_0}\right)\sqrt{P^2+1}\right]}\times \sinh\left[P\left(\frac{t}{l_0}\right)+\sinh^{-1}P\right] \tag{25}$$

However, in this heating problem, what we wish to know is the elevation at any time t of the temperature θ of the inside body above the initial temperature θ_0; that is $(\theta-\theta_0)$, and not $(\theta-T_a)$ as given in equation 25.

Now if we subtract unity from each side of this equation, and multiply both sides by -1, we get

$$\frac{\theta-\theta_0}{T_a-\theta_0}=1-\frac{1}{P}e^{-\left[\left(\frac{t}{l_0}\right)\sqrt{P^2+1}\right]}\times \sinh\left[P\left(\frac{t}{l_0}\right)+\sinh^{-1}P\right] \tag{26}$$

which is in the form desired for the problem of the heating body.

Appendix III

The following analysis considers the time-temperature lag in a thermometer element enclosed in a protecting case immersed in a medium changing in temperature at a constant rate.

Let T_a = temperature of the medium at any time t, and r = the rate of change in the temperature of the medium in degrees per second.

Then the same differential equations apply as were found for a constant-temperature medium as given in Appendix I except that the varying temperature T_a is substituted for the constant temperature T_m and we have from equation 15, Appendix I,

$$\frac{d^2\theta}{dt^2}+\left(\frac{h_1+h_2+l_m}{l_0^2}\right)\frac{d\theta}{dt}+\frac{\theta-T_a}{l_0^2}=0 \tag{27}$$

Assume that the thermometer and medium both start at the same temperature θ_0; then the temperature of the medium at any time t will be

$$T_a=\theta_0+rt \tag{28}$$

The rate r will be positive for increasing temperatures and negative for decreasing temperatures.

Substituting equation 28 in equation 27 we obtain,

$$\frac{d^2x}{dt^2}+\frac{a}{b}\frac{dx}{dt}+\frac{x}{b}=\frac{rt}{b}=\frac{f(t)}{b} \tag{29}$$

where for brevity, $a/b=(h_1+h_2+l_m)/l_0^2$, $b=l_0^2$, and $x=(\theta-\theta_0)$. The integral of an equation of the form of equation 29 in general, as given in any book on differential equations, is

$$x=\frac{1}{\sqrt{a^2-4b}}\left[e^{-\frac{t}{T_1}}\int e^{\frac{t}{T_1}}f(t)dt - e^{-\frac{t}{T_2}}\int e^{\frac{t}{T_2}}f(t)dt\right]+c_1e^{-\frac{t}{T_1}}+c_2e^{-\frac{t}{T_2}} \tag{30}$$

where c_1 and c_2 are constants to be determined, and

$$T_1=\frac{2b}{a-\sqrt{a^2-4b}}=\frac{l_0}{\sqrt{P^2+1}-P}, \text{ and}$$

$$T_2=\frac{2b}{a+\sqrt{a^2-4b}}=\frac{l_0}{\sqrt{P^2+1}+P}$$

In this problem $f(t)=rt$. Substituting the thermal constants corresponding to a and b, and rt for $f(t)$, we have

$$(\theta-\theta_0)=\frac{1}{2l_0P}\left[e^{-\frac{t}{T_1}}\int rte^{\frac{t}{T_1}}dt - e^{-\frac{t}{T_2}}\int rte^{\frac{t}{T_2}}dt\right]+c_1e^{-\frac{t}{T_1}}+c_2e^{-\frac{t}{T_2}} \tag{31}$$

Integrating, collecting terms, and substituting values of T_1 and T_2, we have

$$(\theta-\theta_0)=r\left[t-2l_0\sqrt{P^2+1}\right]+c_1e^{-\frac{t}{T_1}}+c_2e^{-\frac{t}{T_2}} \tag{32}$$

To determine the constants of integration, substitute for T_1 and T_2 and apply the boundary conditions, $\theta=\theta_0$ at $t=0$, and $d\theta/dt=0$ at $t=0$, and we obtain

$$(\theta-\theta_0)=r\left[t-2l_0\sqrt{P^2+1}\right]+\frac{rl_0}{P}e^{-\left[\left(\frac{t}{l_0}\right)\sqrt{P^2+1}\right]}\times\sinh\left[P\left(\frac{t}{l_0}\right)+\sinh^{-1}2P\sqrt{P^2+1}\right] \tag{33}$$

Now instead of the deviation $(\theta-\theta_0)$, of the temperature of the element at time t from the initial temperature as given directly by equation 33, we wish to know the lag, that is $(T_a-\theta)$. We know from equation 28 that $T_a=\theta_0+rt$, and if we substitute in equation 33 the value of θ_0 in terms of T_a and r we obtain the lag at any time,

$$(T_a-\theta)=2rl_0\sqrt{P^2+1}-\frac{rl_0}{P}e^{-\left[\left(\frac{t}{l_0}\right)\sqrt{P^2+1}\right]}\times\sinh\left[P\left(\frac{t}{l_0}\right)+\sinh^{-1}2P\sqrt{P^2+1}\right] \tag{34}$$

The maximum lag results when $t=\infty$, and by substituting this value in equation 34 and evaluating we find that the maximum lag is

$$L=[T_a-\theta]_{max}=2rl_0\sqrt{P^2+1}=r(l_1+l_2+l_m) \tag{35}$$

Dividing equation 34 through by $L=2rl_0\sqrt{P^2+1}$, we have for the equation for increasing temperatures,

$$\frac{T_a-\theta}{L}=1-\frac{1}{2P\sqrt{P^2+1}}e^{-\left[\left(\frac{t}{l_0}\right)\sqrt{P^2+1}\right]}\times\sinh\left[P\left(\frac{t}{l_0}\right)+\sinh^{-1}2P\sqrt{P^2+1}\right] \tag{36}$$

For decreasing temperatures, r becomes negative, and the resulting equation is the same as equation 36 except that $(T_a-\theta)/L$ becomes $(\theta-T_a)/L$. Since r does not appear in the right-hand member of the equations, the form of the lag curve with time is independent of the rate of change in temperature.

The maximum lag can be determined directly from the fundamental differential equation 27, by remembering that at $t=\infty$, $d^2\theta/dt^2$ becomes zero, and $d\theta/dt$ becomes r. Then

$$\left(\frac{h_1+h_2+l_m}{l_0^2}\right)r=\frac{[T_a-\theta]}{l_0^2}\max$$

which results in the same equation 35 as found by the complete analysis, namely:

$$L=[T_a-\theta]_{max}=(l_1+l_2+l_m)r$$

Reference

1. The Compensated Thermocouple Ammeter, W. N. Goodwin, Jr. AIEE Transactions, volume 55, 1936, January section, pages 23–33.

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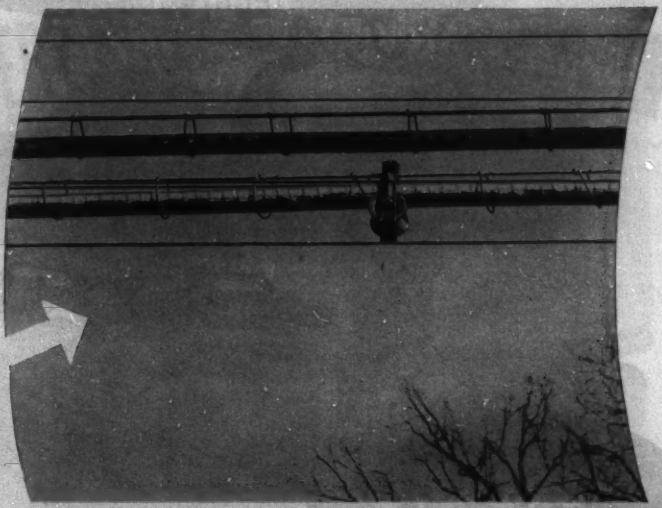

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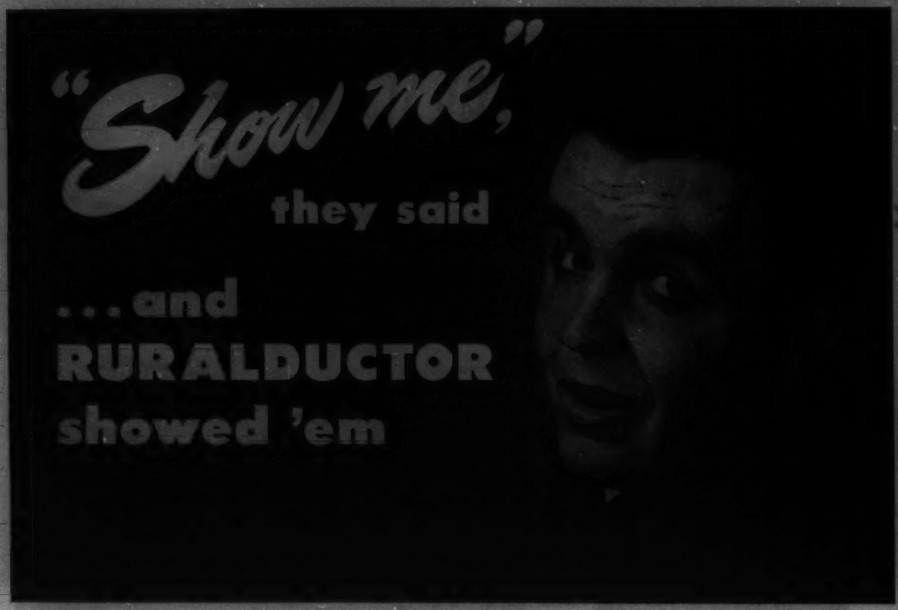

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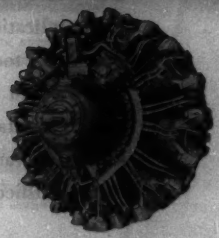

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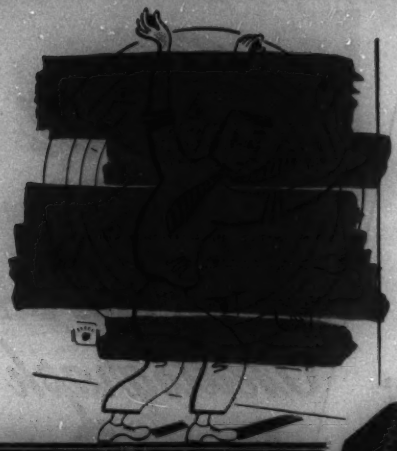

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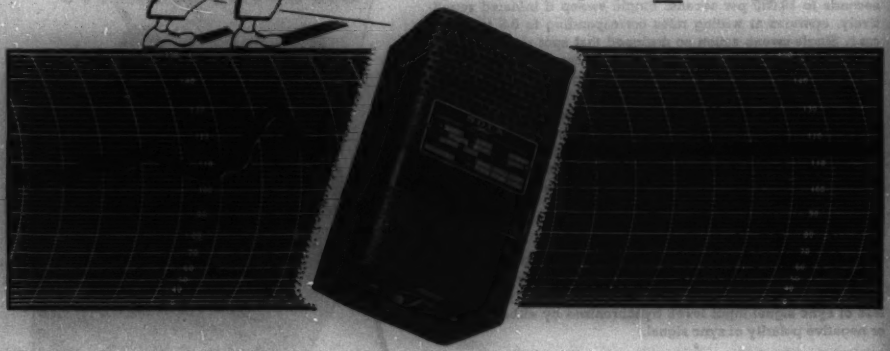

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Complete Information

The New Fiberglas Catalog EL 44-7 contains performance and application data on all types of Fiberglas Electrical Insulation Materials. Anyone concerned with electrical insulation should have a copy—write for yours today. *Owens-Corning Fiberglas Corp., 1859 Nicholas Bldg., Toledo 1, Ohio.*

In Canada, Fiberglas Canada Ltd., Oshawa, Ontario.

FIBERGLAS

*T. M. Reg. U. S. Pat. Off.

ARMY E NAVY

ELECTRICAL INSULATION MATERIALS

PRODUCT OF THE MONTH

From top to bottom of A-C draw-out switchgear section: air circuit breaker in withdrawn, test, and operating positions. With pantograph construction, alignment is automatic; withdrawal is simple.

ALLIS-CHALMERS

METAL-ENCLOSED LOW VOLTAGE SWITCHGEAR

MILWAUKEE, WIS. — Low voltage, metal-enclosed switchgear, featuring pantograph drawout construction, is described by Allis-Chalmers in its new Bulletin B6376.

The Allis-Chalmers pantograph (see photo inset) makes withdrawal of individual breaker elements both simple and quick. With pantograph construction, breaker alignment is automatic; no rail extensions are required; and only a crank is needed to withdraw the breaker!

In low voltage switchgear units, A-C now offers its G-25 circuit breaker — an efficient modern breaker for switching and protecting distribution circuits at 600 volts a-c and below, where 25,000 ampere interrupting capacity is sufficient. Shock and vibration normally encountered won't affect this breaker. It's built simply . . . requires few adjustments.

For outdoor application, Allis-Chalmers totally encloses the switchgear in a weatherproof housing, as shown on opposite page. Thus, rain, snow, and foreign materials are excluded from the switchgear . . . outdoor installation is made perfectly safe.

To get detailed information on Allis-Chalmers low voltage switchgear, contact your nearby A-C district office, or write for Bulletin B6376.

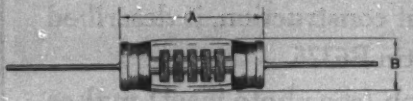
A 1899

MILWAUKEE, WIS.

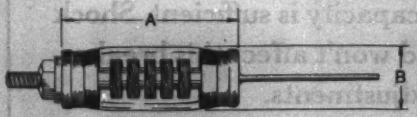
HANOVIA

HERMETICALLY SEALED

R. F. CHOKES



MILLI-HENRIES	A	B
1.0	1-3/4"	5/8"
2.0	1-3/4"	5/8"
2.5	2"	5/8"
5.0	2"	11/16"
10.0	3"	11/16"



AVAILABLE IN ABOVE TWO FORMS
RATED AT 125 M.A. FOR ALL SIZES

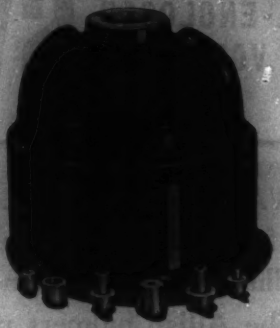
Complete information on these and other Hanovia Chokes on request.

HANOVIA

CHEMICAL & MANUFACTURING CO.

Industrial Division

Dept. EE-3 **Newark 5, N. J.**



BIG INSULATORS

OR SMALL PORCELAIN PARTS

Size of part is no limitation to our facilities. We make large single piece insulators weighing 10 lbs. each or small multiple part insulators in carload lot quantities. In each case Universal "dry process" quality controlled manufacturing methods are maintained. What are your insulator specifications?

THE UNIVERSAL CLAY PRODUCTS CO.
1560 EAST FIRST STREET SANDUSKY, OHIO

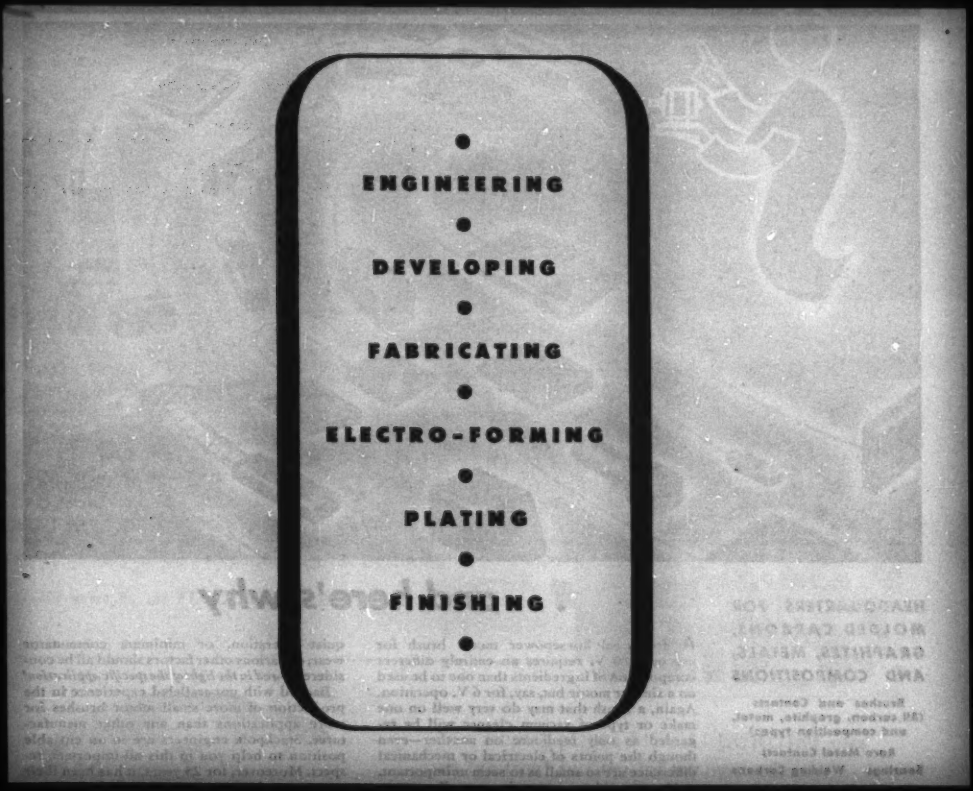
Flexibility of Design

★ and
compactness
with ACRO
★ Switches

● Mechanism of the patented Acro Rolling Spring switch lends itself to adaptation in various shapes to fit the design of your units. Multiple mountings—flat or vertical —end to end, or side by side. Small case shapes— rectangular or curved. Various types of brackets for flexibility of mounting. Actuation pressure as low as two grams (using leaf bracket) or as high as 1¼ lbs. Surely one of the many ACRO Model "M" designs should fit your needs. Send your design details showing space dimensions and operating features for quicker reply.

ACRO ELECTRIC COMPANY
1327 SUPERIOR AVENUE • CLEVELAND 14, OHIO

METAL ASSEMBLIES AND COMPONENTS
FOR
ELECTRONIC AND MECHANICAL DEVICES



BERNARD RICE'S SONS
INCORPORATED

MANUFACTURERS OF QUALITY METAL PRODUCTS SINCE 1867

OFFICE: 325 FIFTH AVENUE, NEW YORK 16, N. Y.

WORKS: 139-145 NORTH TENTH STREET, BROOKLYN 11, N. Y.

EVERY FRACTIONAL HORSEPOWER MOTOR HAS A BRUSH PROBLEM

. . . and here's why

A fractional horsepower motor brush for use on 110 V. requires an entirely different composition of ingredients than one to be used on a similar motor but, say, for 6 V. operation. Again, a brush that may do very well on one make or type of vacuum cleaner will be regarded as only mediocre on another—even though the points of electrical or mechanical difference are so small as to seem unimportant.

Almost without exception, small motors differ in their brush requirements. Even a slight difference in the "mix" of a brush may—and often does—make a whale of a difference in its life or performance. Emphasis on long life, or quiet operation, or minimum commutator wear, or various other factors should all be considered—*and in the light of the specific application!*

Backed with unparalleled experience in the production of more small motor brushes for more applications than any other manufacturer, Stackpole engineers are in an envisible position to help you in this all-important respect. Moreover, for 25 years, it has been their practice to have customers send their equipment to our laboratories. Thus, Stackpole brush recommendations are made NOT by guesswork, but on the sound basis of exhaustive tests on the actual equipment.

HEADQUARTERS FOR MOLDED CARBONS, GRAPHITES, METALS, AND COMPOSITIONS

Brushes and Contacts (All carbon, graphite, metal, and composition types)
Rare Metal Contacts
Bearings Welding Carbons
Packing, Piston and Seal Rings
Continuously Adjustable Carbon Rheostats
Sintered Iron Components
Fixed and Variable Resistors, etc., etc.

STACKPOLE CARBON COMPANY, St. Marys, Pa.

STACKPOLE

THE NATION'S LARGEST PRODUCER OF SMALL MOTOR BRUSHES

In a test cell an ENGINEER studies the performance of a jet-propulsion engine that is expected to produce greater thrust—*for its weight*—than any made in America.

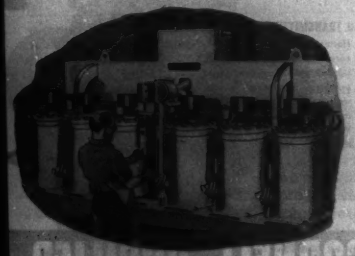
... the name on the J-P ENGINE is Westinghouse.

In a synthetic rubber plant a CHEMIST uses a mass spectrometer to analyze a complex gas mixture by sorting its molecules—reducing analyzing time from *days* to a matter of *minutes*.

... the name on the MASS SPECTROMETER is Westinghouse.

High in the air a SCIENTIST adjusts a fulchronograph which accurately records the *intensity* and *duration* of thunderbolts—in the never ending study of improved protection against lightning.

... the name on the FULCHRONOGRAPH is Westinghouse.



In a refining plant a METALLURGIST uses an Ignitron* rectifier for the more efficient conversion of alternating to direct current—in producing vast quantities of aluminum for our war effort.

... the name on the IGNITRON RECTIFIER is Westinghouse.

*Reg. U. S. Pat. Off.

TODAY—Westinghouse war products are making vital contributions to final Victory over our enemies in the Far East.

TOMORROW—Peacetime products . . . backed by Westinghouse research, engineering and precision manufacture . . . will contribute to greater efficiency in industry and better living in our homes.

Westinghouse

PLANTS IN 25 CITIES OFFICES EVERYWHERE

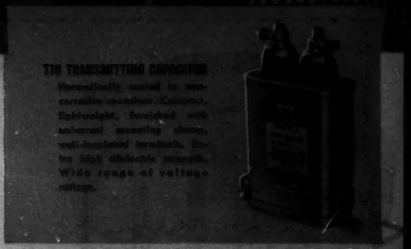
Tune in: JOHN CHARLES THOMAS—Sunday 2:30 pm, EWT, NBC • TED MALONE—Monday through Friday, 11:45 am, EWT, Blue Network

Vigilance in little details is second-nature to C-D craftsmen.

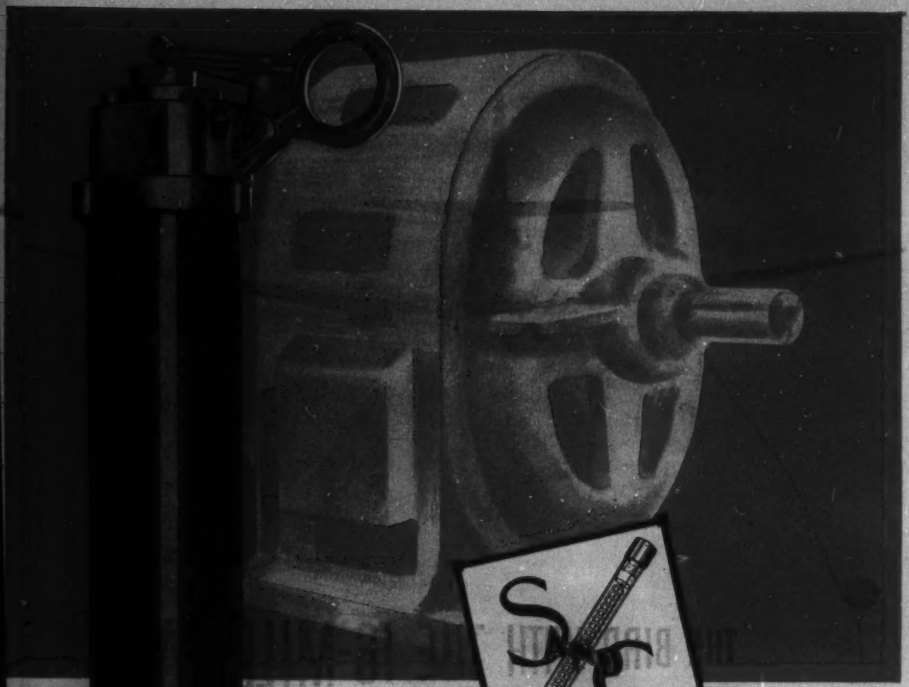
Accuracy is their creed.

With such watchful care, capacitor-building becomes a precise science . . . a science that has earned for Cornell-Dubilier capacitors a world-wide reputation for quality and dependability.

If you have a capacitor problem, you may find the answer in one of our basic innovations in design, engineering or manufacture. Cornell-Dubilier Electric Corporation, So. Plainfield, N. J. Other plants: New Bedford, Brookline, Worcester, Mass., Providence, R. I.



CORNELL - DUBILIER CAPACITORS



Get this better

HI-VOLTAGE MOTOR CIRCUIT

PROTECTION

with Hi-Speed, Hi-Interrupting Capacity

S & C POWER FUSES

Hundreds of up-front heavy industrials find real savings in protection costs and service with these proven-dependable fuses. Designed to interrupt short-circuit current up to 150,000 kva at 2300 volts, their economical, practical protection is gaining rapidly widening acceptance in conjunction with hi-voltage motor control installations.

As the illustration (lower right) shows --these fuses require but little space and are arranged for easy servicing without use of special tools. To replace a blown fuse unit with a new refill is the work of but a few minutes.

It will pay you to get the facts in new Bulletin No. 242. Write for it today.

Fuse at left in disconnect position.

SCHWEITZER & CONRAD, INC.
4427 Ravenswood Avenue, Chicago 40, U. S. A.
Represented in Principal Cities (Consult Telephone Directory)
In Canada by Powerlite Devices, Ltd., Toronto, Ont.

EXPERIENCE WILL CHOOSE AN S&C FUSE

THE BIRD WITH THE 16-MILE TAIL

The wire you see with the parachute on the end of it is a telephone wire, being payed out from a C-47 cargo plane.

Bell Telephone Laboratories, working with the Air Technical Service Command of the Army Air Forces, developed this idea. It will save precious lives and time on the battlefield.

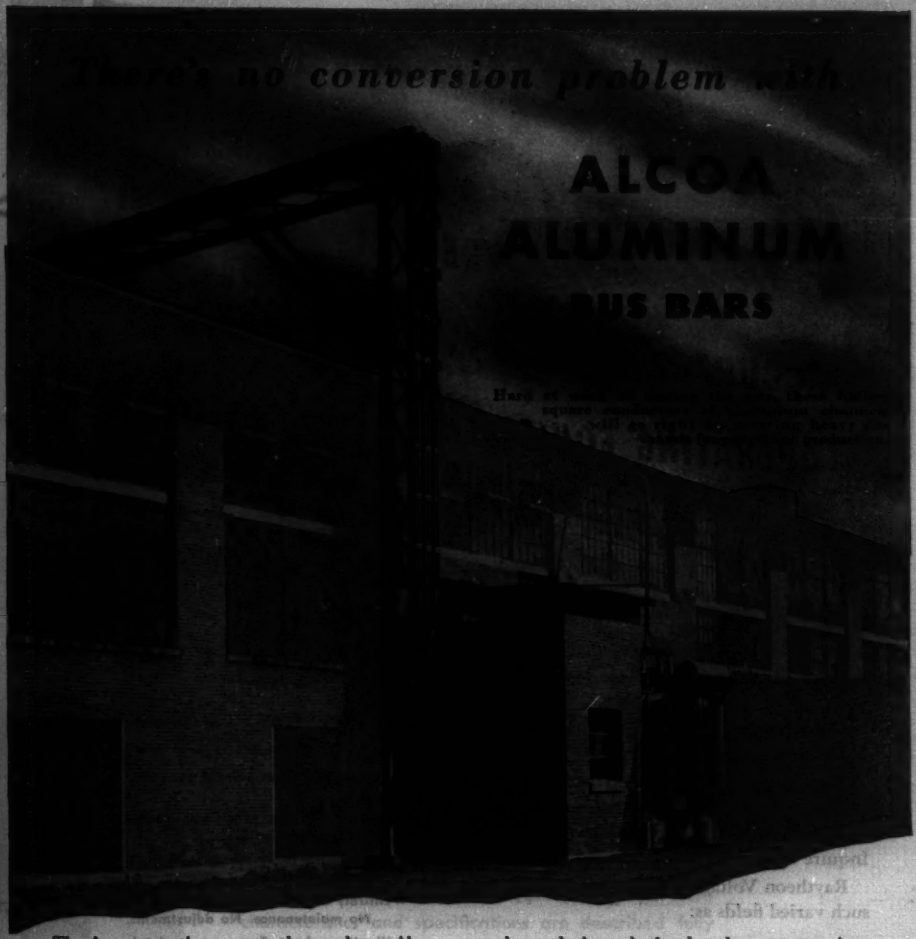
A soldier throws out a parachute with the wire and a weight attached. The weight drops the line to the target area. From then on, through a tube thrust out the doorway of the plane, the wire thrums out steadily — sixteen miles of it can be laid in 6 2/3 minutes. Isolated patrols can be linked quickly with headquarters. Jungles and mountain ranges no longer need be obstacles to communication.

This is in sharp contrast to the old, dangerous way. The laying of wire through swamps and over mountains often meant the transporting of coils on the backs of men crawling through jungle vegetation, and in the line of sniper fire. It is reported that in one sector of the Asiatic theater alone, 41 men were killed or wounded in a single wire-laying mission.

Bell Telephone Laboratories is handling more than 1200 development projects for the Army and the Navy. When the war is over, the Laboratories goes back to its regular job — helping the Bell System bring you the finest telephone service in the world.

BELL TELEPHONE LABORATORIES

Exploring and inventing, devising and perfecting for the Armed Forces at war and for continued improvements and economies in telephone service.



They're energetic war workers, these Alcoa Aluminum bus bars—still delivering power dependably and efficiently for making materials of war. But, let this mill convert to peacetime production and they'll go right on about their business, unaware of the change.

There's no conversion problem, either, in Alcoa's plants on the production of aluminum flats, rounds, angles and channels for bus bar construction.

So, if you're planning to extend old substations or build new ones, Alcoa can now supply you with the aluminum bus bars you'll need—high in conductivity, low in weight, available in any desired shape. Alcoa engineers will gladly help you make a choice. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Bldg., Pittsburgh 19, Pa.

ALCOA ALUMINUM

Step Up THE ACCURACY OF YOUR OPERATING EQUIPMENT with Raytheon Voltage Stabilizers

LINE VOLTAGE may vary between 95 and 130 volts. If not stabilized at the input side of your equipment, this variation can cause highly inaccurate performance.

Get a close-up of the kind of performance your equipment can deliver when teamed with a magnetic-type Raytheon Voltage Stabilizer. Inquire now.

Raytheon Voltage Stabilizers are at work in such varied fields as:

RADIO • TELEVISION • COMMUNICATIONS • RADAR • MOTION PICTURES • SOUND RECORDING • ELECTRONIC DEVICES • CONSTANT SPEED MOTORS • PRODUCTION MACHINERY • SIGNAL SYSTEMS • X-RAY EQUIPMENT TESTING AND LABORATORY EQUIPMENT

Write today for Stabilizer Bulletin DL48-537. Get the story complete.

- ★ Control of output voltage to within ±½%.
- ★ Stabilization at any load within rated capacities from 95-130 V.
- ★ Quick response. Stabilizes varying input voltage within 1/20 second.
- ★ Entirely automatic. No moving parts. No maintenance. No adjustments.
- ★ Won't overheat. Temperature rise is within 55° C.

RAYTHEON
MANUFACTURING COMPANY
WALTHAM 54, MASS.

Presenting

No. 150,003,414

With a war record of more than one hundred and fifty million successful "missions" to their credit, IRC's

BTS INSULATED METALLIZED RESISTORS

have given unquestioned evidence of their complete dependability.

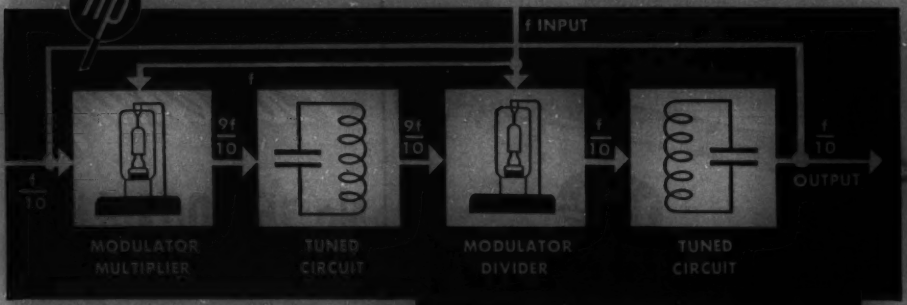
The exact counterparts of these efficient and precision-engineered "veterans" are now available in quantities for your own essential requirements.

Their construction features, resistance-temperature characteristics and specifications are described fully and charted graphically in Bulletin #3 which will be sent to you upon request directed to Dept. 5-1.

• PREFERRED FOR PERFORMANCE •
IRC

INTERNATIONAL RESISTANCE CO.

LABORATORY INSTRUMENTS FOR SPEED AND ACCURACY

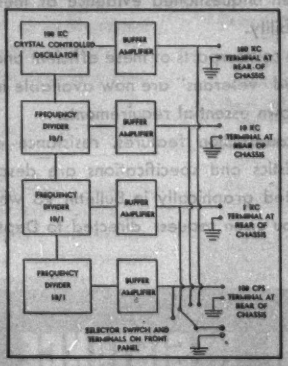


THIS CIRCUIT PROVIDES AN ACCURATE FIXED STANDARD FREQUENCY . . .

A modulator divider tube with a resonant circuit tuned to 1f/10 and a modulator multiplier tube with a resonant circuit of 9f/10 are the fundamentals of a frequency divider unit which is the basic element of this -*hp*- Secondary Frequency Standard.

A small transient voltage in the resonant circuit of the modulator divider tube is applied to the grid of the modulator multiplier tube, and the input voltage f is also applied to this tube. The two voltages mix to supply an output frequency of 9f/10. This frequency (9f/10) is fed to the grid of the modulator divider tube where it is mixed with the input frequency (f), and results in a frequency of 1f/10 in the modulator divider tuned circuit. The action is repeated and the voltage is built up until a stabilized condition is reached or until the frequency (f) is removed. Thus the output of the divider unit is controlled by the input frequency.

Three such frequency divider circuit units in conjunction with a temperature controlled oscillating quartz crystal, which generates 100 kc, make up the -*hp*- 100B Secondary Frequency Standard. By cascading the 100 kc down through the three dividers, accurate fixed frequencies of 10 kc, 1 kc and 100 cps are made available in addition to the 100 kc supplied by the oscillator.


100 KC CRYSTAL CONTROLLED OSCILLATOR
BUFFER AMPLIFIER
100 KC TERMINAL AT REAR OF CHASSIS
FREQUENCY DIVIDER 10/1
BUFFER AMPLIFIER
10 KC TERMINAL AT REAR OF CHASSIS
FREQUENCY DIVIDER 10/1
BUFFER AMPLIFIER
1 KC TERMINAL AT REAR OF CHASSIS
FREQUENCY DIVIDER 10/1
BUFFER AMPLIFIER
100 CPS TERMINAL AT REAR OF CHASSIS
SELECTOR SWITCH AND TERMINALS ON FRONT PANEL

As can be noted by the block diagram, these frequencies are available through a selector switch (on front of panel) or individually from binding posts (rear of chassis). All four fixed frequencies can be utilized at separate test stations simultaneously, which is an economical feature. This instrument is extremely valuable for use in audio and the low radio frequency fields. More complete information will be gladly sent in response to your inquiry. 1072

HEWLETT-PACKARD COMPANY

BOX 1072 · STATION A · PALO ALTO, CALIFORNIA

Audio Frequency Oscillators *Signal Generators* *Vacuum Tube Voltmeters*
Noise and Distortion Analyzers *Wave Analyzers* *Frequency Meters*
Square Wave Generators *Frequency Standards* *Attenuators* *Electronic Tachometers*

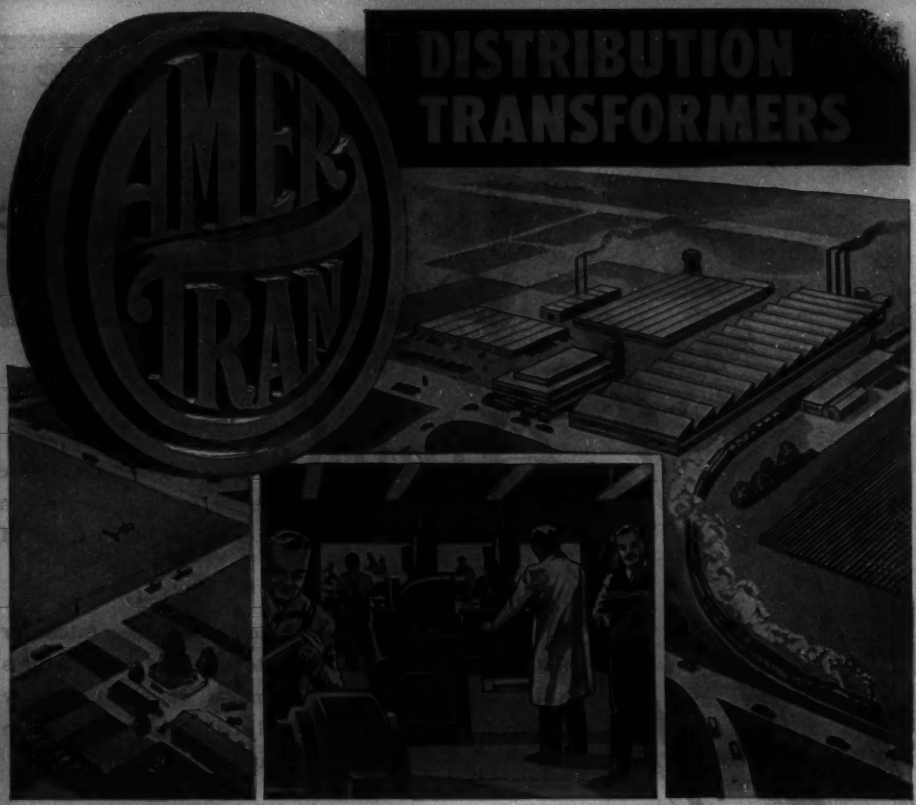
These -*hp*- Representatives are at your Service

Eastern Representatives
Burlingame Associates, Ltd.
11 Park Place
New York 7, N. Y.—Worth 2-5563-4

Midwestern Representative
Alfred Crossley
549 West Randolph St.
Chicago 6, Ill.—State 7444

Western Representatives
Norman B. Neely Enterprises
7422 Melrose Ave.
Hollywood 46, Calif.—Hillside 9135

Canadian Representatives
Atlas Radio Corporation
560 King Street West
Toronto 2, Canada—Wa 4761



FOR THE RURAL INDUSTRIAL PLANT...

Standby equipment and replacement inventories can be carried to an uneconomical point in rural plants. The remedy for this is more dependable equipment. Realization of this fact has caused plant management to prefer the trouble-free durability of AmerTran Distribution Transformers.

Ruggedness has been increased and greater protection has been added to the new AmerTran Distribution Transformers. As a result of their overall economy, the advantages of load center power distribution will cost still less.

AMERICAN TRANSFORMER COMPANY, 178 Emmet St., Newark 5, N. J.

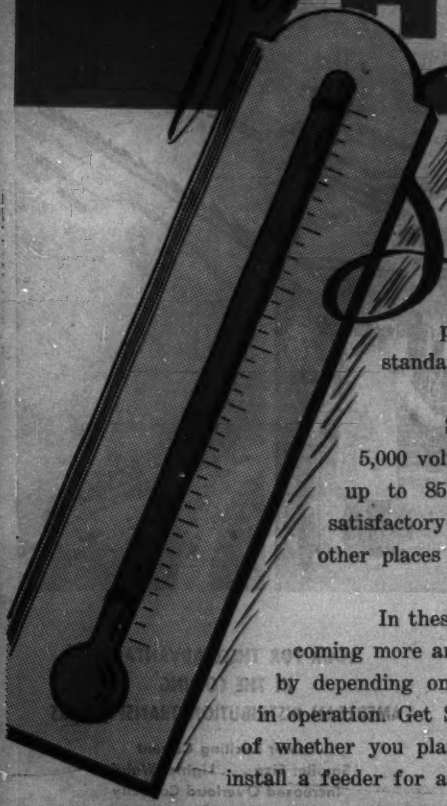
LOOK FOR THESE ADVANTAGES IN THE COMING AMERTRAN DISTRIBUTION TRANSFORMERS

Lower Exciting Current
Smaller Size . . . Lighter Weight
Increased Overload Capacity
Improved Tank Construction
Coordinated Insulation
Improved Regulation
New Terminal Facilities

AMERTRAN

Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

Simplex Varnished Cambric Cables for Hot places



Simplex Varnished Cambric Cables are ideal for use in places where heat deteriorates other types of standard insulations.

Simplex Varnished Cambric Cables rated for 5,000 volts and less can operate safely at temperatures up to 85°C. (185°F.). This makes them particularly satisfactory for mill or factory distribution systems or in other places where heat is an important factor.

In these days when the needs of reconversion are becoming more and more important, don't handicap your plant by depending on old or inadequate cables to keep your plant in operation. Get Simplex Varnished Cambric Cables regardless of whether you plan to completely rewire your plant or merely install a feeder for an addition.

Simplex Wire & Cable Co., 79 Sidney Street, Cambridge 39, Mass.

Simplex

WIRES and CABLES

THE 833A is RCA's most powerful glass triode. With forced-air cooling, under CCS ratings, it will take a maximum input of 1250 watts in plate-modulated service, and 1800 watts in oscillator service—at frequencies as high as 20 megacycles.

Under CCS ratings, with natural cooling, the RCA-833A will take a maximum input of 1250 watts at frequencies as high as 30 megacycles.

Among the applications of this tube are:

1. Radio transmitters, both fixed and mobile.
2. Electronic generators for dielectric heating.
3. Electronic generators for induction heating of small metal parts, such as gears.
4. High-power sound systems.
5. Variable-frequency measuring equipment.

DESIGN FEATURES

100-Watt Thoriated-Tungsten Filament—provides a tremendous emission reserve, which protects against unexpected overloads and adds greatly to filament life.

Giant Zirconium Anode—provides abundant dissipation for high power-output at frequencies up to 30 megacycles. (Maximum of 400 watts CCS rating, with forced-air cooling.)

Filament End-Shielding—special plate construction conserves input power by preventing bulb bombardment.

Post-Terminal Construction—Electronic heating, used in making metal-to-glass seals in the 833A, made possible a compact tube that packs high power into a minimum of space. Post terminals extend through bulb to provide support for electrodes. Results in a rugged construction that lends itself to heavy-duty industrial applications.

Write for Data: For complete technical data on this tube, write to RCA, Commercial Engineering Department, Section 62-35A, Harrison, N. J.

THE FOUNTAINHEAD OF MODERN TUBE DEVELOPMENT IS RCA

RCA

RADIO CORPORATION OF AMERICA

RCA VICTOR DIVISION · CAMDEN, N. J.

PERMANENT MAGNETS MAY DO IT BETTER

(This is the second of three advertisements regarding permanent magnetic materials)

ALNICO ALLOYS (Grades I-IV)

The precipitation-hardening alloys known as Alnico are composed of aluminum, nickel and iron, with the addition of cobalt and copper in some grades. Composition is varied to adapt the material to a wide range of requirements. All grades of Alnico have comparatively high coercive force, moderate residual induction (except Alnico V, which is high in both) and high available energy.

The Alnicos are hard, brittle, coarse-grained, non-forgeable and non-machinable. They are cast from coreless induction furnaces in sizes ranging from 1/10 ounce in weight to 110 pounds. Sintered Alnico is a mixture of powders of the constituent metals molded to desired shapes under extreme pressure. It is less brittle than the cast type, fine-grained, and can be produced in weights between 1/150 ounce and 3 pounds.

Close control of all steps of production is essential for obtaining the highest magnetic efficiency in the Alnico alloys; they must be poured over a narrow range of temperature, heated to just under their melting point for a measured period of time, cooled at a controlled rate and annealed at precisely controlled temperatures.

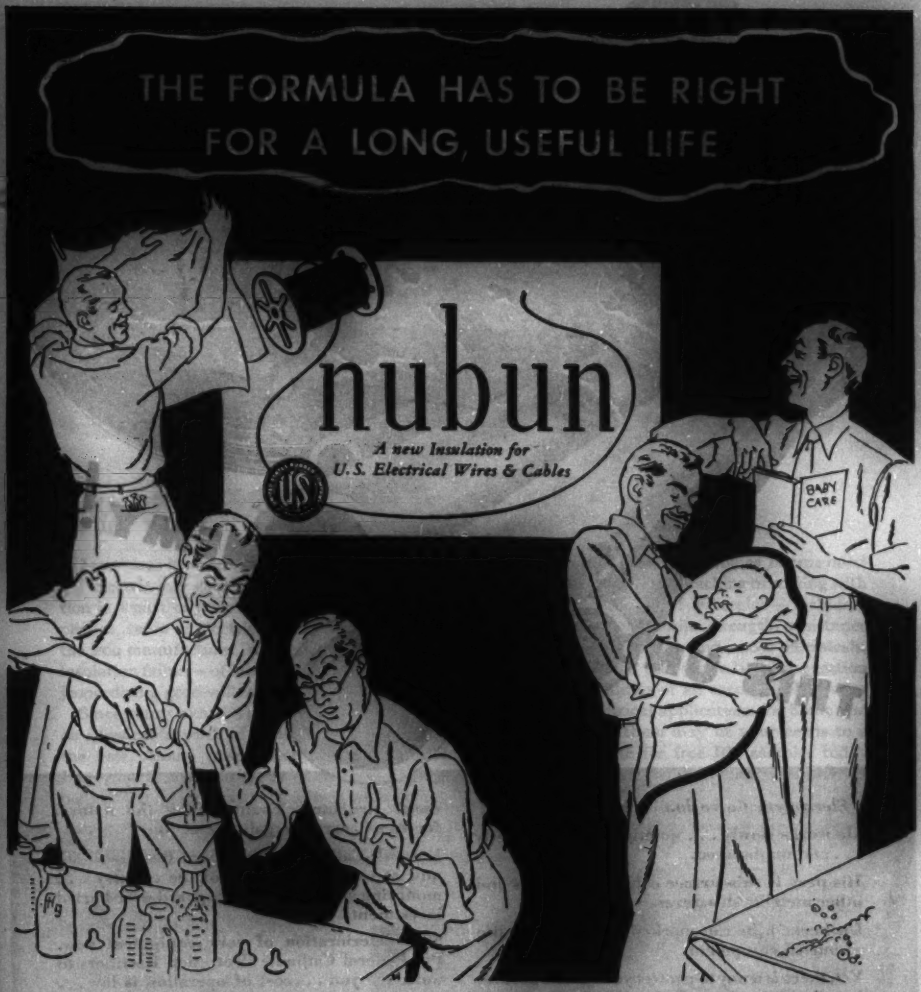
Better permanent magnet materials make possible improved operating results in many devices. Many products now using permanent magnets of less efficient materials should be re-designed to capitalize the latest developments. Consult our engineers on your problems in product design to get the best solution to your permanent magnet requirements. Write for technical handbook: "*Permanent Magnet Manual.*"

★★★ **THE INDIANA STEEL PRODUCTS COMPANY** ★★★

Copr. 1945, The Indiana Steel Products Co.

6 NORTH MICHIGAN AVENUE, CHICAGO 2, ILLINOIS

SPECIALISTS IN PERMANENT MAGNETS SINCE 1910



Only patient, scientific research could have produced a rubber formula combining all the desirable characteristics of Nubun—U.S. Rubber Company's new insulation for wiring.

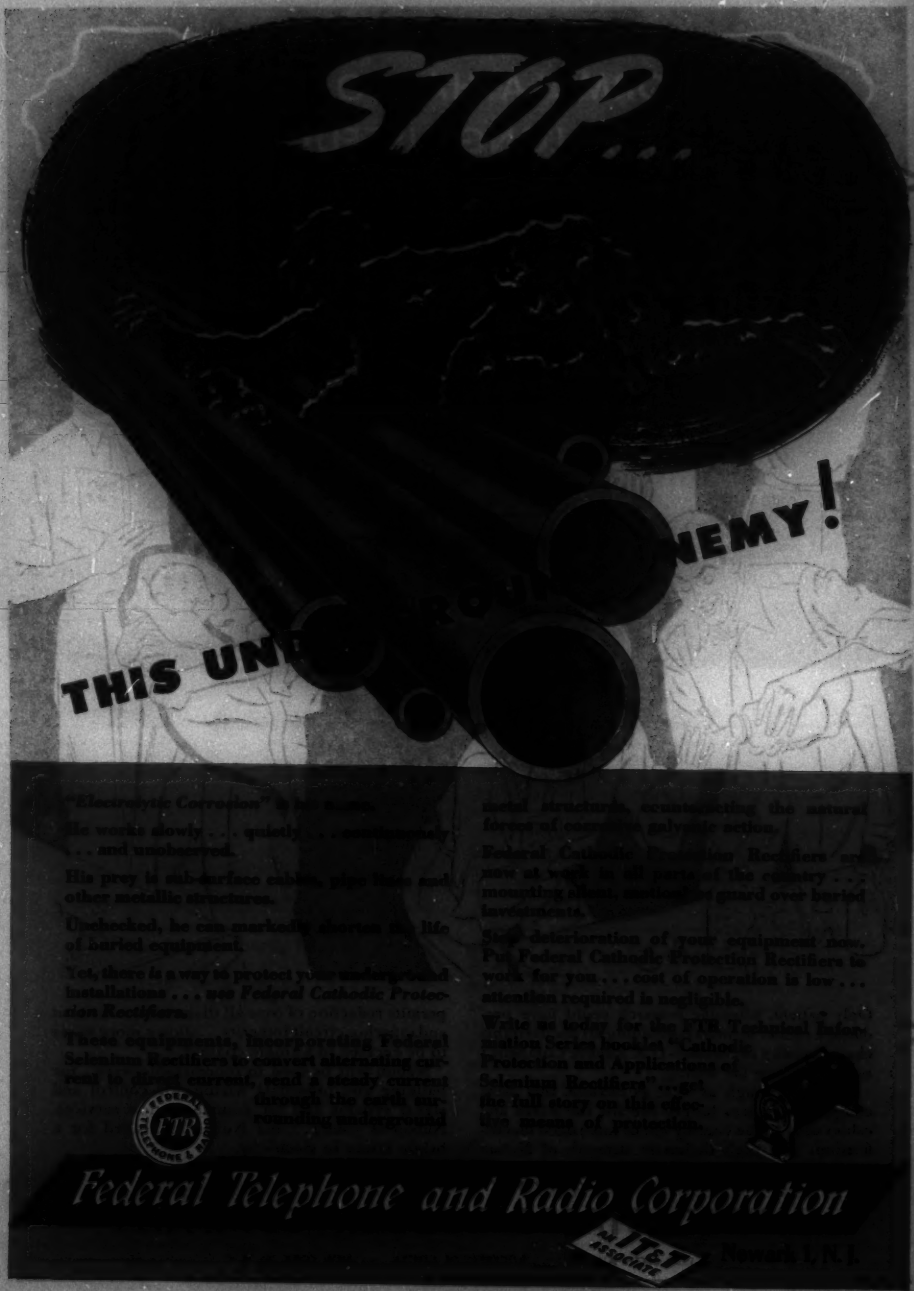
Extremely tough as well as flexible, this buna compound assures longer life for the wires and cables used in the coming era of intensified electrification. The high dielectric strength of Nubun permits reduction of over-all diameters . . . without endangering circuit integrity . . . allows more wires to be encased in a single conduit.

Nubun will be used in innumerable ways . . . for building and industrial wiring, for control and signal systems and for communication services. Nubun is young . . . but Nubun is headed for a bright future in electricity.

Serving Through Science

UNITED STATES RUBBER COMPANY

1230 SIXTH AVENUE • ROCKEFELLER CENTER • NEW YORK 20, N. Y.


STOP...
THIS UN
NEMY!
"Electrolytic Corrosion" is his name.
He works slowly . . . quietly . . . continuously . . . and unobserved.
His prey is sub-surface cables, pipe lines and other metallic structures.
Unchecked, he can markedly shorten the life of buried equipment.
Yet, there is a way to protect your underground installations . . . use Federal Cathodic Protection Rectifiers.
These equipments, incorporating Federal Selenium Rectifiers to convert alternating current to direct current, send a steady current through the earth surrounding underground metal structures, counteracting the natural forces of corrosive galvanic action.
Federal Cathodic Protection Rectifiers are at work in all parts of the country . . . mounting guard, protecting guard over buried investments.
Stop deterioration of your equipment now. Put Federal Cathodic Protection Rectifiers to work for you . . . cost of operation is low . . . attention required is negligible.
Write us today for the FTR Technical Information Series booklet "Cathodic Protection and Applications of Selenium Rectifiers" . . . get the full story on this effective means of protection.
FTR
Federal Telephone and Radio Corporation
A IT&T Associate

WHEN THE INSULATION GOES—

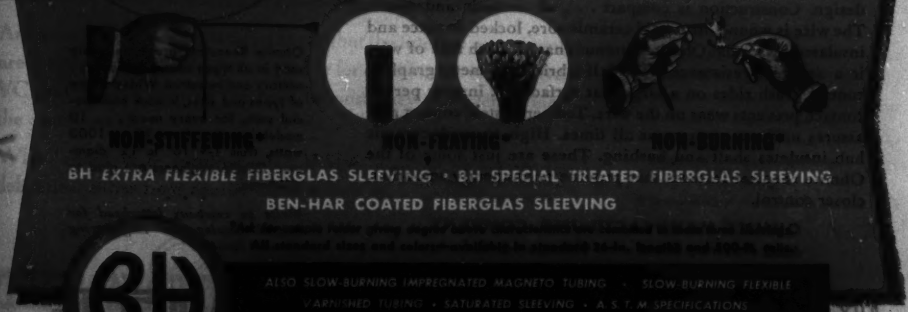
YOUR TROUBLE STARTS!

WHAT does it mean to *you* when Mrs. Smith's electric iron goes *phht?* If electrical insulation is a part of *your* product, whether it's appliance, radio or electrical equipment, you, like the iron manufacturer, run this *risk*. The risk of insulation failure—of inconveniencing customers, jeopardizing good will, and possibly losing sales.

Since your product's performance may depend on a few cents worth of insulation, be sure to use the best. Assure trouble-free service with BH Fiberglas Sleeving, the *original* non-fraying, non-stiffening, non-burning Fiberglas sleeving. An exclusive BH process combines *permanent* freedom from hardening, cracking or rotting with the many advantages of Fiberglas — including high dielectric and tensile strength, resistance to moisture, oil, grease and most chemicals.

Severest wartime uses prove beyond question the superior qualities of all three BH Fiberglas Sleevings in electrical applications for home and industry. One of them may fit your needs to a "T"—*plus!* Write for free BH samples today and put them to the toughest tests your product can dish out!

3 GREAT BH FIBERGLAS SLEEVINGS—EACH 3 WAYS BETTER!



BH *EXTRA FLEXIBLE* FIBERGLAS SLEEVING • BH SPECIAL TREATED FIBERGLAS SLEEVING
BEN-HAR COATED FIBERGLAS SLEEVING

BH PRODUCTS

ALSO SLOW-BURNING IMPREGNATED MAGNETO TUBING • SLOW-BURNING FLEXIBLE VARNISHED TUBING • SATURATED SLEEVING • A.S.T.M. SPECIFICATIONS

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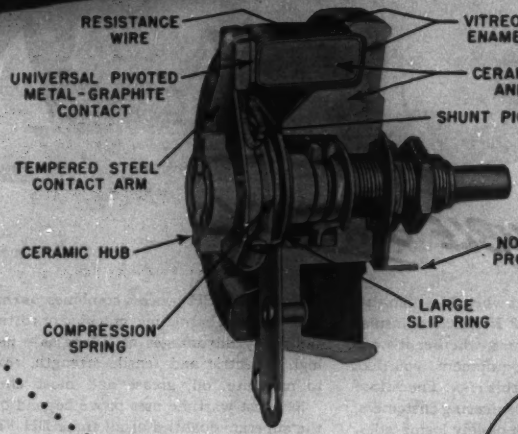
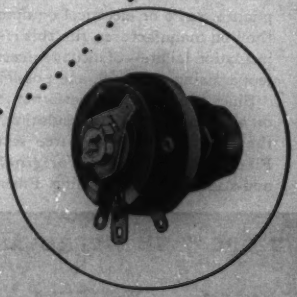
Why OHMITE Rheostats GIVE SMOOTHER, CLOSER CONTROL





DESIGNED AND BUILT TO WITHSTAND
SHOCK • VIBRATION • HEAT • COLD • HUMIDITY

In critical applications, engineers know they can rely on Ohmite design. Construction is compact . . . all ceramic and metal. The wire is wound on a solid ceramic core, locked in place and insulated by special Ohmite vitreous enamel. Each turn of wire is a separate resistance step. Self-lubricating metal-graphite contact brush rides on a large, flat surface . . . insures perfect contact, prevents wear on the wire. Tempered steel contact arm assures uniform pressure at all times. High strength ceramic hub insulates shaft and bushing. These are just some of the Ohmite rheostat features that provide permanently smoother, closer control.

OHMITE MANUFACTURING COMPANY
4803 Flournoy Street • Chicago 44, U. S. A.

Ohmite Rheostats are extensively used in all types of applications . . . military and industrial. Widest range of types and sizes, in stock and special units, for every need . . . 10 models ranging from 25 to 1000 watts, from 1-9/16" to 12" diameter. Ohmite engineers are glad to assist you.

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Write on company letterhead for helpful Catalog and Engineering Manual No. 40.

BUY MORE WAR BONDS

Be Right with OHMITE

RHEOSTATS • RESISTORS • TAP SWITCHES

Hermetic Sealing Demands Top-Quality Components

Hermetically sealed transformer manufactured by Acme Electric & Mfg. Co. of Cuba, N. Y. . . . Part-by-part assembly view shows E-lamination and I-lamination stacks; assembled coil, insulated with Natvar VC, and with Natvar sleeving on all leads; complete chassis; and completed transformer in hermetically sealed case.

Acme builds transformers to pass the rigid Navy 5 cycle immersion test for hermetically sealed units. Because they are used on important equipment for the Armed Forces, it is essential that quality material be used throughout. *These transformers dare not fail!*

And so every precaution is taken to see that the internal components are far above the standards acceptable for ordinary service. Natvar VC and Natvar sleeving are used because they consistently meet the requirements.

What about *your* requirements? Write, wire or phone us for deliveries, either from nearby wholesaler's stock, or from our own.

Natvar

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- Varnished cable tape
- Varnished canvas
- Varnished duck
- Varnished cellulose acetate
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- Varnished Fiberglas cloth
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- Varnished tubings and sleeving
- Varnished identification markers
- Lacquered tubings and sleevings
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- Extruded vinyl identification markers

Write for Catalog No. 20

THE NATIONAL VARNISHED PRODUCTS Corporation

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203 RANDOLPH AVENUE ★ WOODBRIDGE NEW JERSEY

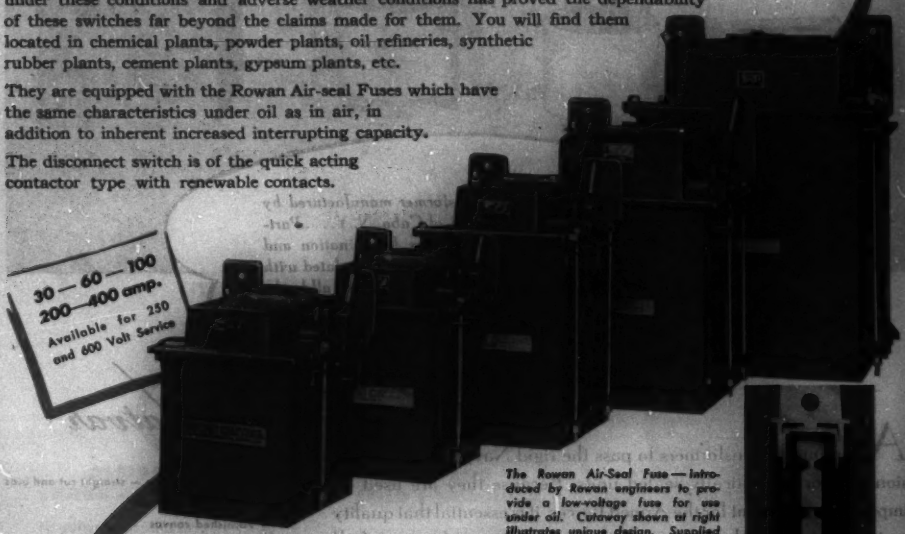
FOR MAXIMUM SAFETY AND CONTINUITY OF SERVICE

Rowan COMPLETELY OIL IMMERSED, FUSED, SAFETY LINE DISCONNECT SWITCHES

Designed and time-tested for locations where the atmosphere is contaminated with corrosive elements, semi-hazardous and hazardous vapors and dust. Continuity of service under these conditions and adverse weather conditions has proved the dependability of these switches far beyond the claims made for them. You will find them located in chemical plants, powder plants, oil refineries, synthetic rubber plants, cement plants, gypsum plants, etc.

They are equipped with the Rowan Air-seal Fuses which have the same characteristics under oil as in air, in addition to inherent increased interrupting capacity.

The disconnect switch is of the quick acting contactor type with renewable contacts.



The Rowan Air-Seal Fuse — introduced by Rowan engineers to provide a low-voltage fuse for use under oil. Cutaway shown at right illustrates unique design. Supplied in 30—60—100—200—400 amp., 250 and 600 Volt.

Other features of the Rowan Oil Immersed Disconnect Switch are:

1—ROWAN AIR-SEAL fuses. **2**—Completely oil immersed. **3**—Disconnect switch of the quick acting contactor type with renewable contacts. **4**—Safety enclosing case mechanically interlocked to prevent lowering of tank when switch is in operating position or closing of switch when tank is lowered. **5**—Enclosing case is weather-resisting and dust-tight. **6**—PROVISION for locking disconnect switch in "off" position. **7**—Tank handles for ease of handling.

The Rowan Controller Company has specialized in Oil Immersed Controls for nearly half a century. Results and performance achieved by users justify the Rowan claim of superiority in this field. Write for complete information on Rowan Oil Immersed Controls.

ROWAN CONTROL

and you can trust it Inside O-B BUSHINGS

PORCELAIN, whose dependability is so high that you take it for granted in all of your line insulation, is *inside* O-B bushings for the same reason, and with the same results. When you have O-B bushings on your apparatus, your power is porcelain-insulated right to the windings of the equipment; and with O-B porcelain-insulated bushings, you get the performance and durability that you have learned to expect from this rugged dielectric. Only in O-B bushings do you get porcelain insulation *clear through*--porcelain protection right to your apparatus windings. Specify the only porcelain-insulated bushings--O-B--on your next equipment.

Ohio Brass

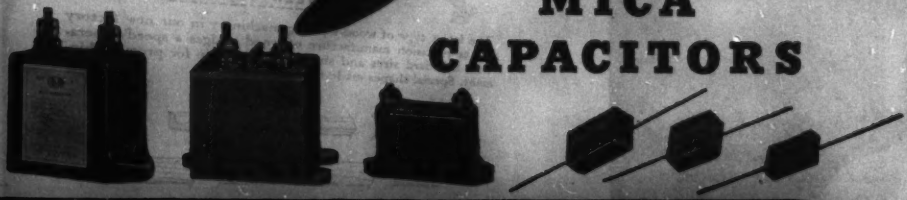
MANSFIELD, OHIO, U. S. A.

CANADIAN OHIO BRASS COMPANY, LTD., NIAGARA FALLS, ONTARIO

HOW EXCELLENCE IS

SANGAMO ELECTRI

BUILT INTO Sangamo MICA CAPACITORS



COMPANY SPRINGFIELD ILLINOIS

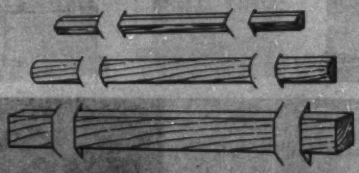
"Wedgie" Announces

THE OPENING OF OUR NEW FACTORY AT

ESCANABA, MICHIGAN

IN THE HEART OF THE HARD MAPLE VENEER COUNTRY

The latest type of wood-working machinery in our new factory makes precision manufacture of wood wedges a speedy operation. Standard sizes and shapes are available for prompt shipment. Special shapes made to order.



9 FEATURES SPEED YOUR PRODUCTION . . . .

1 Production in our new factory assures uniform quality and delivery.

2 Only well-seasoned, straight-grained, hard maple used in manufacture.

3 Straight-grained stock provides extra strength, reduces breakage.

4 Precision-set saws to accurate dimensions to fit every slot of standard slot.

5 Tumbled in paraffin to remove splinters and provide wax coating.

6 Wax finish permits wedges to slide into position easily and quickly.

7 Large assortment of standard sizes means every normal need.

8 Low percentage of wastage due to precision manufacturing.

9 Lower in price than hand sliced stock readily available.

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RESISTANCE WELDING Will Speed Peacetime Production Too

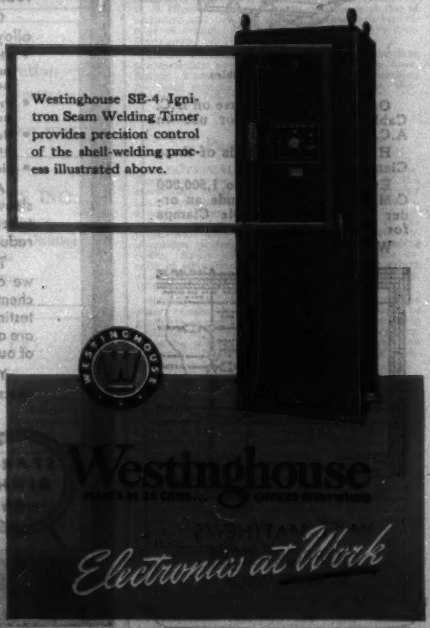
Behind every battle at the front, are many battles on the production line. For example, the battle for shells—a battle resistance welding has helped win by speeding production of uniform, dependable shell cases.

On machines such as that shown above, millions of shell cases have been assembled. Developed by a leading resistance welder manufacturer, the machine welds the circular base to the cylindrical shell, providing a gas and flame-tight seal, at the rate of several hundred per hour.

Unprecedented production rates were obtained by using two station fixtures in conjunction with Westinghouse SE-4 Ignitron Seam Welding Timers. This setup enables the operator to remove a finished shell and insert parts for the next unit while the machine automatically welds a shell in the other station.

Constant production schedules, month after month, and the unusually rigid inspection standards, proved the dependability of Westinghouse Timers under these most severe operating conditions.

If you work with metal, investigate how resistance welding may help you speed production, reduce costs, provide more dependable and uniform products. Westinghouse engineers are ready to help you explore the possibilities of using this process. Just call your nearest Westinghouse office. Westinghouse Electric Corporation, P. O. Box 868, Pittsburgh 30, Pennsylvania. J-21359



Westinghouse SE-4 Ignitron Seam Welding Timer provides precision control of the shell-welding process illustrated above.

SAVE $5.00 A TURN OR DEADEND

on 000 to 1,500,000 C.M. cable with

Matthews Cable Clamps

Shows how strain caused by right angle taps can be relieved

Outside Turns, Straight Guys

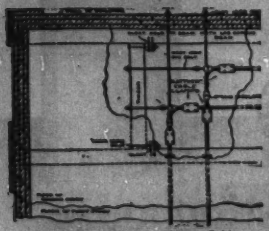
Deadending Two Cables

Order Number 2 for use on D.C. Cable or Number 3 for use on A.C. Cable.

Hundreds of thousands of these Clamps have been sold.

Every order for 000 to 1,500,000 C.M. Cable should include an order for Matthews Cable Clamps for every corner or deadend.

Write for Bulletin C.



Right Hand Turns in Heavy Cable

W. N. MATTHEWS CORPORATION

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Radio and Radar . . . antenna tuners, wave guides and stabilizers . . . function at new high levels of efficiency because of laminated precious metal tubing and solid coin silver tubing.

The entire Electrical Industry has been quick to recognize the fact that laminated precious metal tubing maintains delicate electrical properties without variance under any climatic or atmospheric conditions. It is therefore ideal for electronic applications, high frequency radio parts and delicate instrument assemblies.

Gold, silver, platinum and palladium or special precious metal alloys laminated to base metal have made these things possible . . .

- **The desirable electrical, mechanical or chemical qualities of the precious metals have been added to the strength or other desirable properties of base metals, precisely where and as required.**
- **Precious metal properties of corrosion resistance, electrical superiority, and durability are obtained without solid precious metal costs.**
- **Uniform maintenance of lamination ratios with no porosity, pit marks or defects.**
- **Finer, more lasting finishes than are otherwise obtainable in base metals.**

Almost every conceivable shape of tubing may be had. Rings, sleeves and jackets are quickly and economically cut from laminated tubes. Machining and forming operations can often be eliminated or reduced by the use of specially shaped tubing.

To assist you in the application of our products to your products we are maintaining a staff of thoroughly experienced metallurgists, chemists, designers and consultants . . . an up-to-date research and testing laboratory . . . and a splendidly equipped tool room. These are all at your service to cooperate with your own staff to the full extent of our facilities.

Your inquiries are cordially invited. Ask, too, for a copy of our new descriptive folder.

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FABRICATED PARTS AND ASSEMBLIES

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ELECTRICAL AND MECHANICAL. *Electrical* needed with diagram experience; *Mechanical* needed with detail and layout experience on machinery. Work in Pittsburgh area. Write Westinghouse Electric Corporation, Industrial Relations, 4N17. Give full details of experience, education, age, present salary, and salary expected.

Engineering Societies Personnel Service, Inc.

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All replies should be addressed to the key numbers indicated and mailed to the New York Office

Men Available

ELEC-MECH ENGR; graduate; 20 yrs des. constr, and opern; 17 yrs in responsible charge. Exper covers heavy machinery, diesel-generation, substations up to 110 KV, pumping systems, etc; last 2 yrs Chief E.E. for large industrial. E-104.

ELEC ENGR; 28; exper in designing and supervising elec maint, constr of industrial plants and pwr houses. Can operate elec dept of large industrial plant efficiently and economically. Any location. E-114.

REGISTERED ELEC ENGR; 48, married; exper design, layout industrial light and pwr; supervision, inspection on constr; maint engr, charge motor repair, rewind; opern steam and Diesel pwr plant. E-115.

ENGR; 20 yrs exper supervising installation, maint, rehabilitation and operation of elec eqpt. Exper covers diversified eqpt from large rotating machinery to controls, and includes the associated masonry and steel structures. E-116.

ELEC ENGR; college grad; 20 yrs exper; 11 yrs elec eqpt design, industrial and automatic substa control. Aptitude mech and circuit design. Exper supervising. Desires pos with responsibility and future. E-117.

ELEC ENGR; 55, married; long European-American exper pwr, light, electronics, presently U. S. Navy ship design, seeks position with use of technical and business exper and thorough knowledge of French, Russian and German. Available September. E-118.

ELEC ENGR, Ph.D.; age 28; desires associate professorship and exec pos in a western univ. Exper: 2 yrs high-voltage research, 3 yrs teaching pwr and communications, 1½ yrs indus electronics. E-119.

Positions Available

ELECTRICAL ENGINEERS. (a) Electrical Engineers to be trained for patent work in the electronics field, particularly radio. Apply by letter submitting complete details of education, experience and salary requirements. (b) Graduate Electrical Engineer having experience in the preparation and prosecution of U. S. patent applications, preferably in electrical fields, including radio. Apply by letter submitting complete details of education, experience and indicate salary expected. Location, vicinity of New York City. W-5759.

SALES ENGINEER, 30-45, for Diesel electric plants ranging from 300 KW upwards. Should be graduate electrical engineer with aggressiveness in addition to technical knowledge and experience. Must be willing to travel the world as occasion demands. Headquarters, New York, N. Y. W-5806.

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ELECTRICAL ENGINEER experienced in motor control applications to variable torque, variable speed, variable tension, industrial machine drive. Requires an intimate knowledge of rotating machinery, amplifiers, electronic motor control, selsyn and synchro-tie. Salary, from $4800 a year. Some traveling. Permanent. Headquarters, New York, N. Y. W-5843.

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Simplified

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Electronics

Provided by

VIBROTEST

INSULATION RESISTANCE TESTER

ELECTRONICS—one of the revolutionary factors in electrical industry—calls for most accurate testing of insulation resistance in most practicable form. VIBROTEST has long proved its dependable precision with sturdiest construction—

With Synchronous Vibrators dependable for top performance—longest service.

With self-contained power source, 2 No. 6 dry cells of highest quality mounted in base. (Replacements obtainable anywhere.)

With easiest operation. No cranking. No leveling.

MODEL 201

One of 36 Vibrotest Models, covering every service.

Model 201 for general duty has a range of 0-200 megohms at 500 volts potential, 0-2000 ohms, 150-300-600 volts AC or DC. Compact, versatile, portable. Strong metal case, complete with cover and leather strap handle for carrying.

SEND FOR COMPLETE BULLETINS

Ask about new Model 238 calibrated 20,000 megohms at 500 V. DC, attaining a new high in precision insulation resistance testing equipment. Also HYPOT Insulation breakdown tester. VIBRO-GROUND for ground resistance measurements, VOLTAMMETER for both A.C. voltage and amperage, etc. Research and development engineering.

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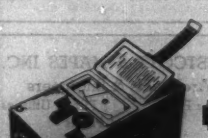
The registered trade-mark "Megger" is not the name of any single device; it is neither adjective nor noun; of itself, it has no generic or descriptive meaning. "Megger" is simply the mark or symbol identifying a specific brand of insulation testers, megohmmeters, ground testers, ohmmeters and other measuring and testing devices.

"Megger" Insulation Testers

"Meg," "Super-Meg" and Midget types to meet practically all requirements for testing insulation resistance of electrical equipment. Ratings up to 2000 megohms and 1000 volts d-c. Hand-cranked generators always ready for use. 500-volt models are most popular. *Bulletins 1735-EE and 1785-EE.*

"Megger" Ground Testers

Undoubtedly the most simple and reliable devices ever developed for measuring resistance to earth of ground rods, metal structures and other ground connections. Hand-cranked generators. Ranges as low as 0 to 3 ohms and as high as 0 to 30,000 ohms. *Catalog 1645-EE.*



"Megger" Ohmmeters

Illustrated is the low resistance "Ducter" type for switch, circuit breaker and contact resistances, direct indicating down to .000001 ohm. Operated by storage battery. "Ducter" measurements identify incipient trouble and forestall failure. *Bulletin 1635-EE.*

★ Three important electrical maintenance tools . . . direct indicating . . . simple to operate . . . rugged and highly dependable . . . generally accepted for maximum reliability and economy in field use.

Let us explain why and how "Megger" instruments are used in testing and maintenance work; why there is a place for them in nearly every electrical equipment maintenance routine.

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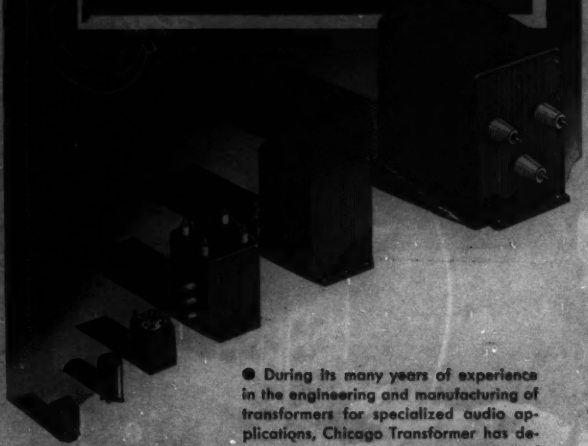

Also makers of . . .
Power transformers for radio and other electronic circuits, vibrator power transformers, audio and filter reactors, instrument transformers, auto and control transformers, wave filters, fluorescent ballasts and ignition coils.

● During its many years of experience in the engineering and manufacturing of transformers for specialized audio applications, Chicago Transformer has designed and produced a wide variety of types, from the tiny units used in walkie-talkies to large size modulation transformers. If you have a design problem involving transformers in audio or other types of circuits, let this well qualified organization be of service to you.

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Search Warrant for Spring Trouble

Spring coiling can, and often does, become a very complicated and vexing problem where both machine and material must yield peak performance in order to meet critical dimensional and test specifications.

Then ordinary methods of analyzing the product deviations and its many possible causes are out. Only unusual technical skill supported by advancing instrumentation can succeed in obtaining the desired solutions.

All of the many special electronic devices used in regular production and for special investigations are designed and constructed by Hunter's Special Apparatus Division. If you agree we go to more trouble to make springs right than you expected of leading springmakers, we can only say—you haven't seen anything yet.

HUNTER PRESSED STEEL COMPANY, LANSDALE, PENNA.

An invitation to all electrical designers to

TRY SILVER GRAPHALLOY

FOR BRUSHES

High current density, low contact drop, low electrical noise, and self-lubrication are characteristics of this silver-impregnated molded graphite that may be the answer to your electrical brush problems.

FOR CONTACTS

Low contact resistance and non-welding when breaking surge currents are inherent properties of this unique combination of conductive silver and self-lubricating graphite.

SLIP-RING AND COMMUTATOR

BRUSHES AND CONTACTS

SAMPLES of Silver Graphalloy will be gladly furnished for test on your applications. Silver Graphalloy is usually silver plated to permit easy soldering to lead springs or holders. Why not WRITE NOW for your test samples?

ALWAYS SPECIFY GRAPHALLOY

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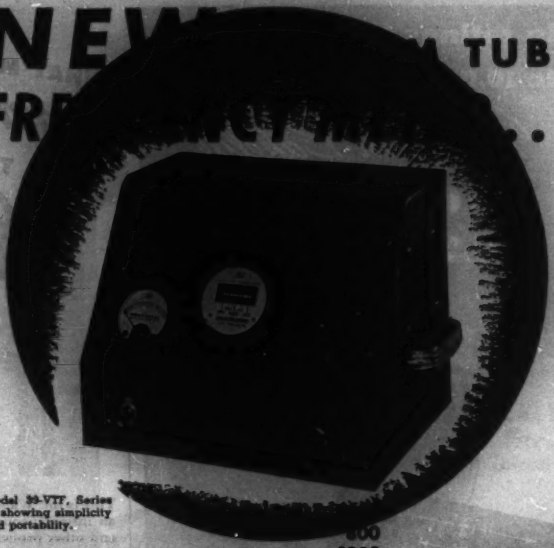


Model 39-VTF, Series A, showing simplicity and portability.

... FOR FREQUENCIES IN 300 1200 1600 2400 3600 CYCLE BANDS

MODEL 39-VTF, Series A, a new development of J-B-T engineers, measures frequencies in six specific bands with accuracy of ± 0.25% of the frequency being measured, and with sufficient amplitude to be easily read.

Vacuum tube multivibrator circuits divide the incoming frequency by 1, 2, 3, 4, 6 or 9, depending on the position of the multiplier switch, and show the result on the time-tested, standard 400 cycle meter.

Regular line current is used for power supply, permitting an input sensitivity of 500,000 ohms. Response is not affected by irregular wave form, nor by harmonic content of unknown frequencies of less than 10% or 15% . . . and input control permits use from 100 to 350 volts.

The result is an instrument of high accuracy and high stability with permanent calibration . . . especially useful for checking audio oscillators, frequency converters, radar equipment, and for standardizing less accurate frequency measuring units.

Check These Points

- **EXTREME ACCURACY** . . . within ± 0.25% of frequency being measured.
- **PERMANENT ACCURACY** . . . no further calibration or standardization required at any time.
- **STABILITY** . . . no temperature drift after initial 30 second warm-up.
- **BURN-OUT PROOF** . . . no protection needed against accidental above-range frequencies.
- **SENSITIVITY** . . . 500,000 ohms.
- **SIMPLICITY** . . . uses standard tubes.
- **POSITIVE SWITCHING** . . . built-in switch is J-B-T's own rugged, coin-silver plated instrument switch, as supplied for high quality testers.

New Booklet . . . just off press, illustrates other types of J-B-T Vibrating Reed Frequency Meters. Ask for Bulletin VF-43-1C.

J-B-T

Manufactured under J-B-T and/or Triplett Patents and Patents Pending 8-JBT-4

In ratings from 1000 volts to 10,000 volts test

Molded-in-Bakelite

MICA CAPACITORS

Standard units with tapped holes take 6/32 screws for terminals. Also available with clearance holes for screws or rods, for stock mounting.

● The 1650 Series is the most rugged of the heavy-duty molded-in-bakelite mica capacitors of the extensive Aerovox line. These high-voltage units are intended for the most critical service of low-powered transmitting circuits, buffer stages, power amplifiers, laboratory equipment, etc. Also for use in ultra-high-frequency circuits, and accordingly their r.f. current ratings are given in the Aerovox Catalog.

The extra-generous use of high-grade dielectric material provides that greater factor of safety for longer service under severest operating conditions. Available in low-loss (yellow) XM bakelite.

In 1000, 2500, 5000, 7500 and 10,000 volts D.C. test. Capacitance ratings from .00005 mfd. to .06 mfd. in Type 1650 at 1000 v. D.C. test; .00005 mfd. to .001 in Type 1654L at 10,000 v. D.C. test.

● **Literature on request . . .**

AEROVOX *Capacitors*

INDIVIDUALLY TESTED

WHAT MAKES UP AN *'Iron Constitution'* IS REVEALED WITH THE HELP OF *Cannon Plugs*

This is the Waugh Metal Analyzer (above and below). It gives an instantaneous indication of the hardness, grain structure and other properties of ferrous materials on which it is used. It performs this scientific feat by means of magnetic analysis and employs many precise electric circuits in its hook-up. These circuits are connected and test units are plugged in through various Cannon Connectors—indicated in the rear view of the open cabinet. Both plug and receptacle types are shown.

Wherever you need a quick, positive and secure connection in the electric circuits of the instruments you use or the products you manufacture, use Cannon Connectors. There are thousands of stock styles and sizes to choose from and a staff of experienced engineers to develop special Cannon Connectors for your use if need be.

A Type "K" Cannon Connector with integral clamp is pictured at left. Write for a Type "K" Cannon Catalog to get a general introduction to this Cannon line. Address Department A-118, Cannon Electric Development Company, 3209 Humboldt Street, Los Angeles 31, California.

CANNON ELECTRIC

Cannon Electric Development Company
Los Angeles 31, California

Canadian Factory and Engineering Offices:
Cannon Electric Company, Limited, Toronto

Representatives in Principal Cities—Consult Your Local Telephone Book

First with GRADE 1, CLASS 1 RESISTORS

(First produced Dec. 1941—Millions made to date)

First with RESISTORS WOUND with CERAMIC INSULATED WIRE
(Pioneered and perfected by Sprague many years ago)

First with GLASS-TO-METAL SEALED RESISTORS (Pioneered by Sprague in 1941, now produced commercially at the rate of thousands of seals per day)

First with GLAZED CERAMIC SHELLS and New Style End Seals for 5-, 10-, 25-, 50- and 120-watt resistors. (One type of Koolohm—the *standard* type—does the job under any climatic condition, anywhere in the world)

First and STILL EXCLUSIVE with MEGOMAX (The high-resistance, high-voltage resistors. Megohms of resistance operated at thousands of volts!)

One after another, Sprague Koolohm Resistors have established new performance records as proved indisputably by the record. One after another Koolohm Resistors have revolutionized traditional limitations to wire wound resistor usage—because radically different Koolohm construction permits a higher degree of physical protection, better electrical characteristics, smaller sizes, and easier mounting arrangements than are possible with conventional resistor types. Write for catalog.

SPRAGUE KOOLOHM
WIRE WOUND RESISTORS

SPRAGUE ELECTRIC COMPANY
(Resistor Division) North Adams, Mass.

E·T·L TEST REPORTS

CONFIRM USER'S EXPERIENCE WITH

KAPPA TAPES

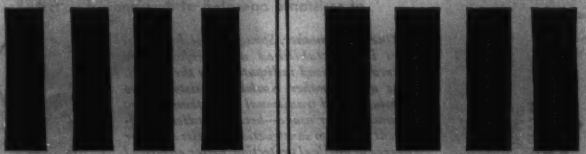
LESS VARNISH BUILD-UP

COTTON UNVARNISHED	VARNISHED 2 DIPS BLACK VARNISH	KAPPA UNVARNISHED	VARNISHED 2 DIPS BLACK VARNISH
.8.85 MILS	13.5 MILS	7.6 MILS	8 MILS

Kappa Tape takes substantially less varnish build-up and conserves maximum space for copper. On the samples mentioned above, the cotton weighed 8.4 oz. per 100 yards before dipping and 24 oz. after dipping, showing a gain of 15.6 oz. per 100 yards. Kappa Tape weighed 8.3 oz. per 100 yards before dipping and 14.7 oz. after dipping, showing a gain of only 6.4 oz. per 100 yards. In addition to important space saving, Kappa Tape also provides real economy of varnish. (The cotton tape used throughout test was the type customarily used for coil winding and was supplied by a major electrical manufacturer.)

UNIFORM AND *MORE COMPLETE* IMPREGNATION

Unretouched photograph of test samples prepared by Electrical Testing Laboratories using comparable cotton and Kappa Tape samples.



COTTON SAMPLES AFTER 2 VARNISH DIPS — KAPPA SAMPLES AFTER 2 VARNISH DIPS

Because of the nature of the material and its freedom from surface fibres, KAPPA Tape has inherently superior varnishing characteristics, resulting in a uniform unbroken membrane essentially free from pinholes and irregularities. The samples above photographed by transmitted light clearly demonstrate this . . . show one reason why KAPPA tests so high in dielectric and why KAPPA wound coils are uniformly superior in performance as well as appearance.

HIGHER DIELECTRIC

Partly because the cellulose acetate material is itself a high dielectric and partly because of superior varnishing characteristics as shown above, KAPPA Tapes when impregnated with standard varnishes by standard methods show an exceptionally high dielectric, with fewer varnish dips than normally specified for other materials. Here, for example, are AVERAGE figures for comparable cotton and KAPPA Tapes with 2 dips of varnish, 10 tests per sample.

AVERAGE DIELECTRIC BREAKDOWN COTTON 3,195
AVERAGE V. P. M. COTTON — 245

AVERAGE DIELECTRIC BREAKDOWN KAPPA 12,000
AVERAGE V. P. M. KAPPA — 1,510

Many Kappa users have reported that they are getting equivalent or superior insulation results with as much as 50% fewer dips than previously specified . . . with resultant savings in time and material.

Such performance certainly suggests that you thoroughly investigate this new and better electrical Tape. Write us for the Kappa bulletin including complete test data and for long length samples for your own experiments.

WM. E. WRIGHT & SONS COMPANY
Box 1500, West Warren, Mass.

KAPPA CELLULOSE-ACETATE RAYON COIL WINDING TAPES

The Wright Tape for every winding . .

I-T-E unit substation design offers extra advantages

By constructing the transformer and switchboard elements of unit substations in one piece, completely enclosed, I-T-E brings additional benefits to the unit substation user. No field assembly is necessary, throat connections and alignment problems are eliminated. Installation consists merely of connecting external circuits.

Furthermore, I-T-E Unit Substations are designed to exactly meet the customer's needs, rather than to approximate his requirements . . . and at no extra cost.

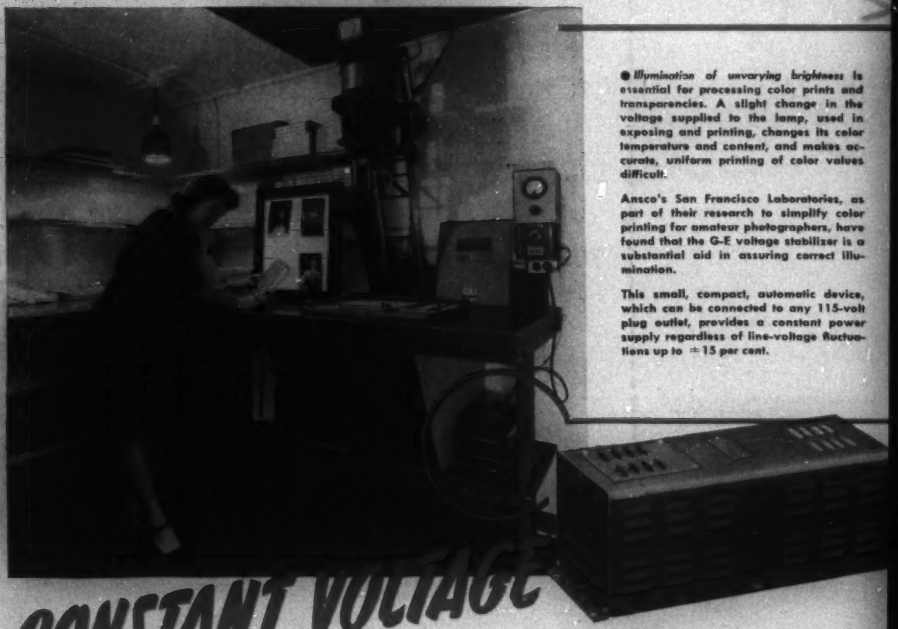
The complete job is engineered as a single unit, fully backed with undivided responsibility by I-T-E. To summarize, this assures you of increased safety, simplified installation and improved appearance.

For full details on the many advantages of I-T-E Unit Substations, call your nearest representative or write to I-T-E Circuit Breaker Company, 19th & Hamilton Streets, Philadelphia 30, Pennsylvania.

This Multumite Unit Substation, containing the foregoing described equipment, provides protection, improves operation and reduces power costs for a large manufacturer.

I-T-E AIR SWITCHGEAR

ANSCO Gets Better Color Prints with G-E Voltage Stabilizer



● *Illumination of unvarying brightness* is essential for processing color prints and transparencies. A slight change in the voltage supplied to the lamp, used in exposing and printing, changes its color temperature and content, and makes accurate, uniform printing of color values difficult.

Ansco's San Francisco Laboratories, as part of their research to simplify color printing for amateur photographers, have found that the G-E voltage stabilizer is a substantial aid in assuring correct illumination.

This small, compact, automatic device, which can be connected to any 115-volt plug outlet, provides a constant power supply regardless of line-voltage fluctuations up to ±15 per cent.

CONSTANT VOLTAGE

may add new accuracy to your precision jobs, too

● On almost every precision job where electricity is used, a closely held voltage supply adds speed or accuracy, or decreases rejects. In addition, it protects delicate instruments, tools and electronic tubes from sudden overvoltages, and increases the reliability and life of such equipment.

If you are a user or manufacturer of such apparatus as radio transmitters, testing equipment, X-ray machines, other electronic devices, motion-picture projectors, and precision photographic equipment, it will pay you to investigate the benefits of G-E voltage stabilizers. They can be used as an accessory to present equipment or built into new, redesigned products to add salability.

These small, compact units are available in ratings from 50 to 5000 va. On circuits where the voltage may vary from 95 to 130 or 190 to 260 volts, they automatically provide a constant 115- or 230-volt output. Because they have no moving parts, the need for maintenance is practically nonexistent. Ask for Bulletin GEA-3634A for complete information. *General Electric Company, Schenectady 5, N. Y.*

Buy all the BONDS you can — *and keep all you buy*

GENERAL ELECTRIC